BEHAVIOR OF WTEE BEAMS IN FLEXURE

by

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ABSTRACT

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The current US steel building specifications (ASD and LRFD) make the fundamental assumption that constituent cross-sectional plate components of WTEEs in flexure do not buckle as individual elements. Rather, any buckling that occurs during bending is more global in nature. However, new research and experiments (Corona and Ellison 1997, 1997a, 1998) are proving that this is an oversimplification, and refute the current assumptions. The main objective of the current study is to investigate the general response and governing limit states exhibited by WTEE beams at their maximum load. Recommendations are subsequently made for changes to the current US steel building design specifications as they pertain to the flexural response of WTEEs.

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This work is dedicated to my father, and my guardian angel, Charles Andrus. He taught me that I could do anything that my heart desired.

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1.0 INTRODUCTION

WTEE beams are typically made by slicing a hot rolled W shape in half length-wise; thereby producing two individual T shaped steel members known as a WTEE. These sections are most commonly used as chord members in both roof and floor trusses. In this application, the mono-symmetric structural shape is subjected to both axial and flexural loads. It is imperative that the member has the ability to resist the applied bending loads. The bending resistance can be achieved either through having the stem in compression and the flange in tension, or the converse.   In the present research, the former case will be considered only.

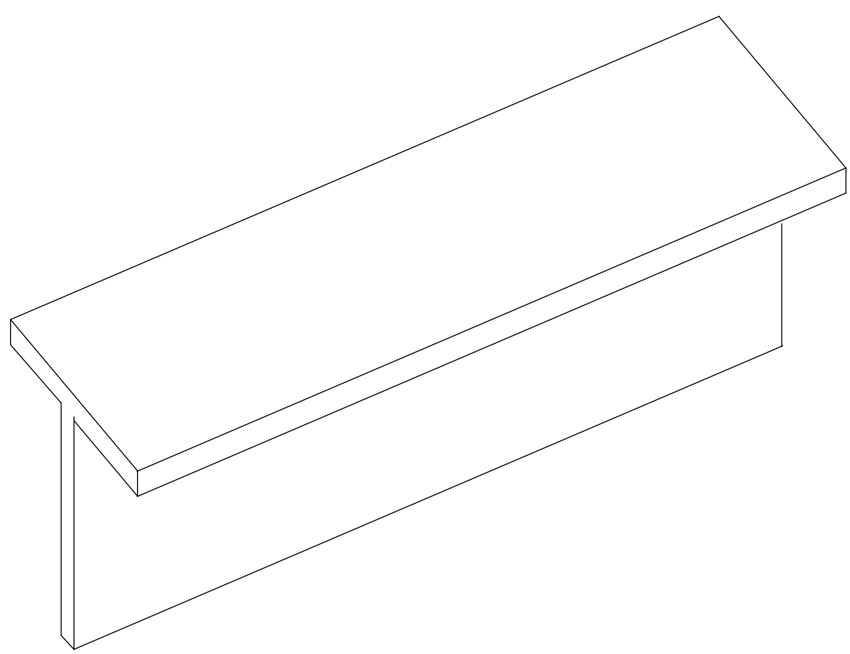


Figure 1 Illustration of WTEE Beam

Buckling during flexure can be classified into three major categories, lateral-torsional buckling, local buckling, or distortional buckling. Lateral-torsional buckling is the simultaneous out-of-plane deflection and twisting of the beam without deformation of the cross section. Long beams generally buckle in a lateral-torsional buckling (LTB) mode. The wavelength of the buckling wave for LTB is the longest of the three types of flexure induced instability.

Local buckling is generally plate buckling in the flange and/or web of the beam without overall lateral deflection or twisting. Any significant deformations are limited to a small region along the length of the beam (i.e. local buckling is a short wave-length manifestation).

Distortional buckling is an intermediate wavelength mode involving characteristics consistent with a combination of the two foregoing buckling modes. Distortional buckling is the simultaneous occurrence of lateral deflections and cross sectional distortion at buckling. Short beams with slender webs are quite susceptible to this buckling mode. The buckling characteristics depend on a variety of geometric and loading parameters.

The current US steel building specifications (ASD and LRFD) make the fundamental assumption regarding the governing response of WTEE beams that plate components of the WTEEs do not buckle as individual elements. Rather, any buckling that occurs due to bending is more global in nature. However, new research and experiments (Corona and Ellison 1997, 1997a, 1998) are proving that this is an oversimplification, and refute the current assumptions.

Rotation capacity is one measure of structural ductility, or deformation capacity, defined by ASCE as $R=\{(\vartheta_u / \vartheta_p)-1\}$ where ϑ_u is the rotation when the moment capacity drops below M_p on the unloading portion of the M-ϑ plot and ϑ_p is the theoretical rotation at which the full plastic capacity is achieved based on elastic beam stiffness.

This definition is described graphically in Figure 2. In this figure, ϑ_1 corresponds to ϑ_p, and ϑ_2 corresponds to ϑ_u in the ASCE definition.

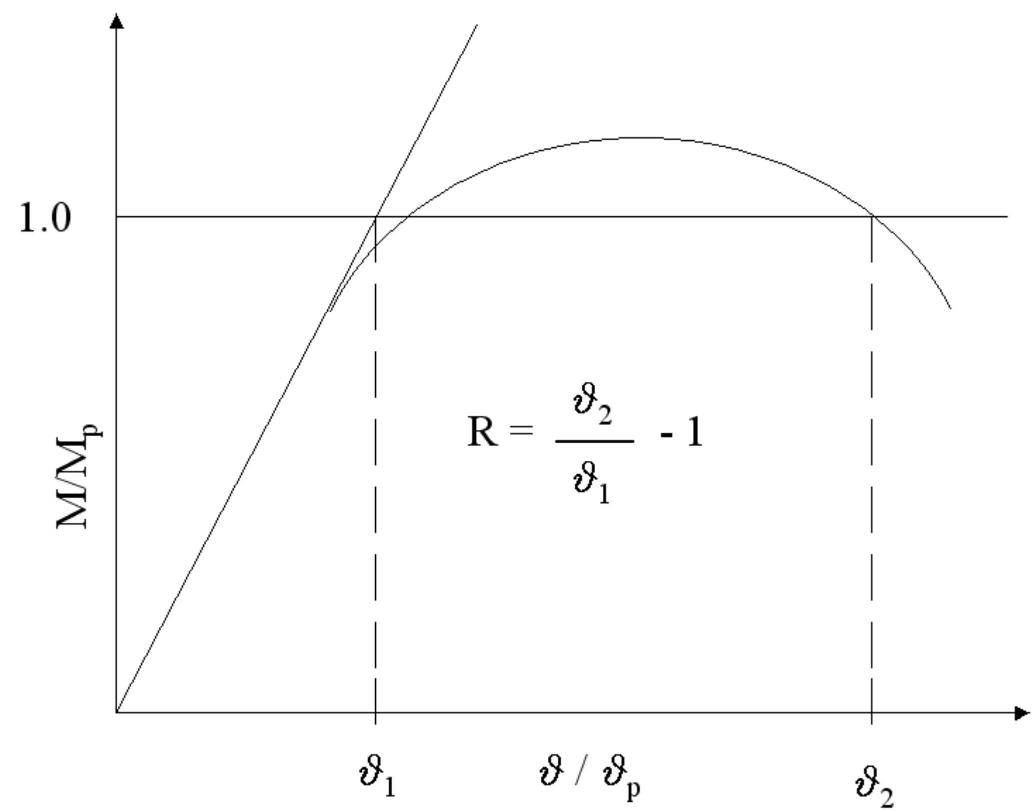


Figure 2 Definition of Rotation Capacity

The main objective of the current study is to investigate the general response and governing limit states exhibited by WTEE beams at their maximum load. Information on cross-sectional rotation capacity will be used to make recommended changes to the current US steel building design specifications.

1.1 Background and Literature Review

WTEE sections are most commonly used as chord members in both roof and floor trusses. In this situation, the mono-symmetric structural shape is subjected to both axial and flexural loads. Detailed, basic research on the response and buckling of such structural members within the plastic range of the material of the steel material response is relatively sparse. The current US steel building specifications (ASD and LRFD) make the fundamental assumption regarding the governing response of WTEE beams that cross-sectional plate components of the WTEEs do not buckle as individual elements. Rather, any buckling that occurs due to bending is more global in nature. However, new research and experiments (Corona and Ellison 1997, 1997a, 1998) are proving that this is an oversimplification, and refute the current assumptions.

Mark S. Ellison and Edmundo Corona (1997) have cooperatively explored the behavior of WTEE beams in flexure. They set out to prove that long beams buckle in a Lateral Torsional Buckling (LTB) mode while short beams buckle locally due to large distortions of the flanges and web. It was also believed that the sign of the bending moment (tip of the web in tension or compression) would influence the buckling load and mode. A series of experiments were conducted on the plastic buckling and collapse of WTEE-beams under pure bending. Comparisons between the experimental and numerical results were made to verify results.

The experiment utilized A36 hot-rolled structural steel plates built-up into a WTEE shape. The nominal dimensions of the shape were as listed:

- $b = h = 36mm(1.5")$
- $t_w = t_f = 4.8mm(3/16")$
- $\frac{h}{t} = 8$
- $\frac{L}{h}$ Ranged from 7.5 to 20

Negative moment was induced in the WTEE, thereby putting the stem in compression (see Figure 3).

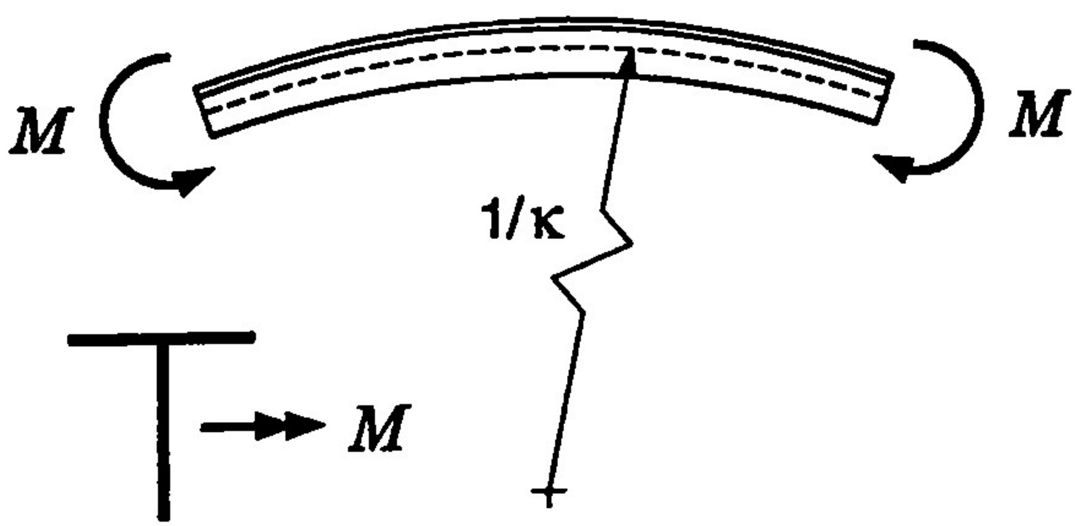
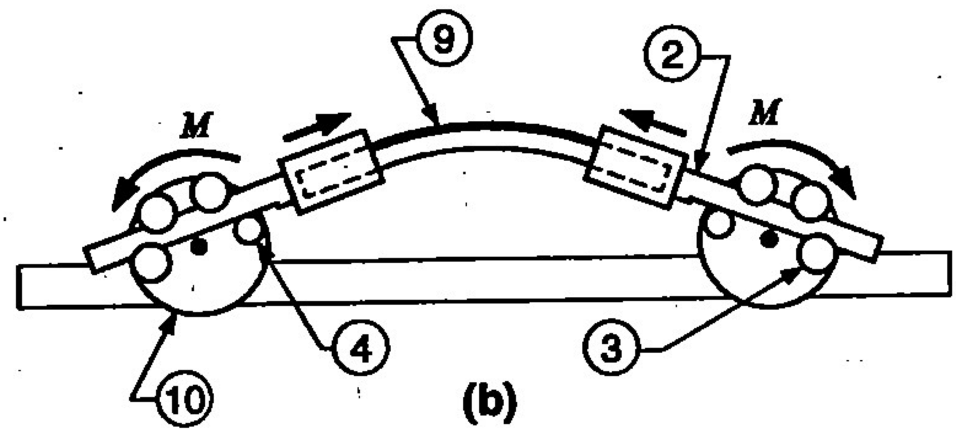


Figure 3 Negative Moment Induced Upon WTEE Beam

The experimental apparatus was designed with four main considerations, to maintain flexibility, simplicity, low cost and to maximize accuracy and completeness of the measurements. This apparatus consisted of four major parts: a servo-hydraulic, four-point bending device with closed-loop control; grips that transfer the load from the bending device to the specimen; an instrument used to measure the deformations of the beam induced by buckling; and a computer-based data acquisition system.



KEY (In alphabetical order)

1 – CHAIN	6 – LOAD CELL
2 – CLAMP ASSEMBLY	7 – RVIT
3 – CURVED ROLLER	8 – SERVO-VALVE
4 – FLAT ROLLER	9 – SPECIMEN
5 – HYDRAULIC CYLINDER	10 – SPROCKET

Figure 4 Bending Machine as Developed by Corona and Ellison

The boundary conditions employed in the experiment allowed no displacements along the y and z-axes (as defined in Figure 5). Additionally, no rotations about the x and z-axes were allowed at the beam-ends. The rotations about the y-axis at the two nodes were equal and were the prescribed loading variables. Translation along the x-axis was prevented at the junction of the flange and the web at the mid-span of the beam.

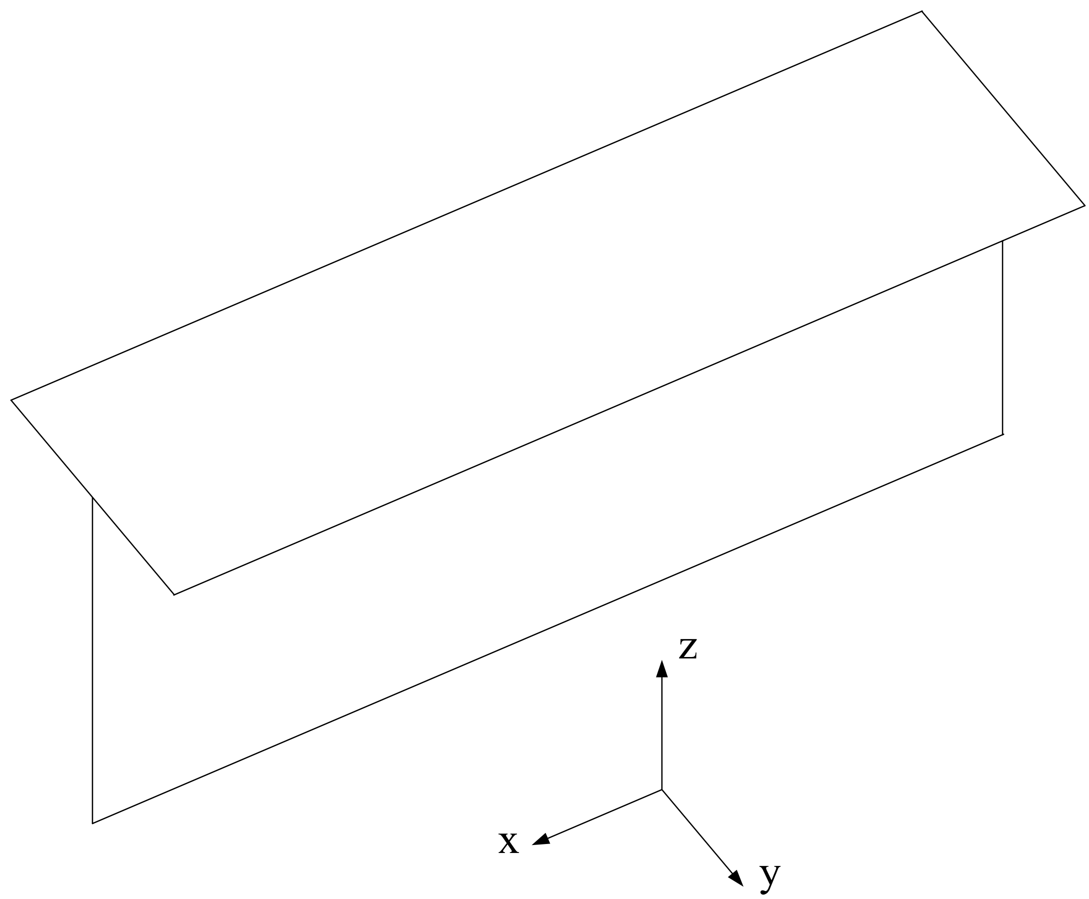


Figure 5 Coordinate System Employed by Corona and Ellison

The setup allowed the specimen to be subjected to pure bending and the direction of bending could be reversed in order to be able to prescribe cyclic bending histories employing full loading reversal. The sum of the rotation of the sprockets was directly proportional to the displacement of the actuators. The device naturally operated in a manor in which the sum of the rotation of the sprockets was the control variable. Rotation of the sprockets was measured independently using rotary variable inductance transducers (RVIT's). The measurements were represented by $k = \frac{\vartheta_1 + \vartheta_2}{L}$ where ϑ_1 and ϑ_2 are the rotations at the two sprockets. Throughout the experiment, the values of moment, curvature, and torque were recorded every time the curvature changed by 0.004 m^{-1} (0.001 in^{-1}) or the moment changed by 2.3 N*m (20 lb*in).

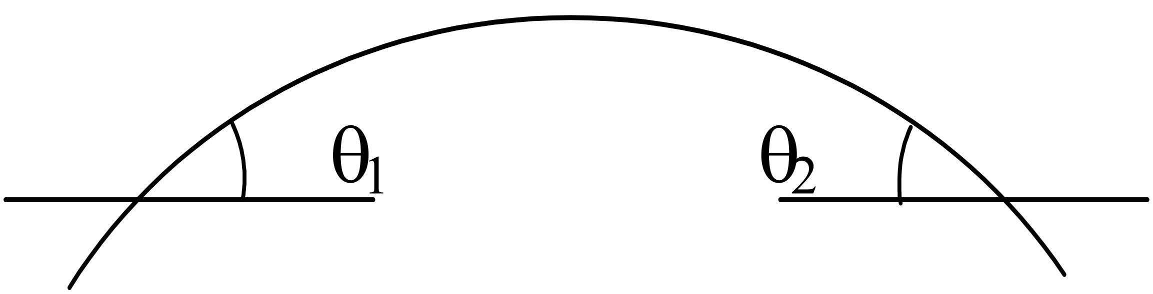


Figure 6 Measurement of Rotations

The results produced by the experiment were compared with numerical results obtained from a finite element model of the experimental specimen. The commercial code ABAQUS was employed to carry out the finite element analysis.

The beams were discretized using S4R nonlinear shell elements. These are shear-flexible, reduced integration, quadrilateral shell elements, which allow for large rotations and finite strains. The two ends of the beam were modeled with rigid elements, R3D4. These elements create rigid bodies with the same cross-sectional geometry as the beam. Rigid body reference nodes were defined at the centroid of the cross section between the two rows of rigid elements at both ends of the mesh. The rigid ends were used to replicate the ends of the beam, which were secured in the experimental apparatus. The boundary conditions applied to the model were identical to those in the experimental model.

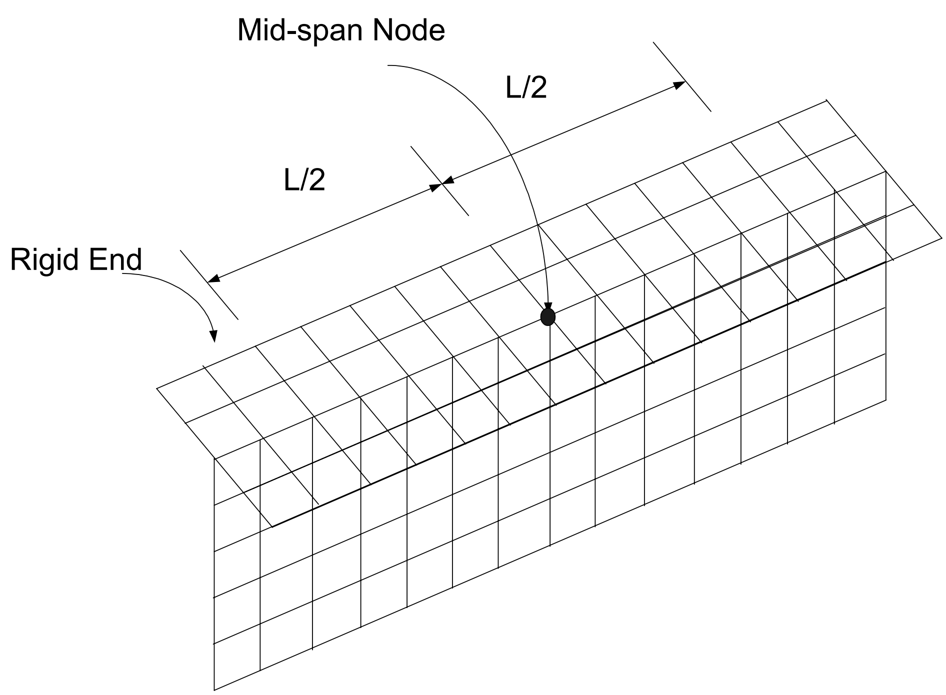


Figure 7 Discretized Model

The physical experiment produced results that indicated that the collapse modes of the beams had components of lateral-torsional buckling and distortion of the web to different degrees. Special attention was paid to the role that the deformation of the cross section played in the response, buckling and collapse of the beams. It was found that the deformation of the cross section depended on the direction of the bending and affected the M-K (moment-curvature) response. If the beam was bent with the tip of the web in tension, significantly higher curvatures were achieved before collapse and no local buckles formed in the curvature range tested. Collapse occurred at relatively low curvatures when the tip of the web was in compression. In this case, a ripple developed in the deflection of the web in all cases considered. This ripple, however, did not have a well-defined wavelength, and was strongly influenced by the initial deflection of the web prior to loading. The ripple could be detected at nearly the same curvature ($K/K_1 \approx 1$) in all specimens despite variations in length. Initially, the amplitude of the ripple grew uniformly with curvature along the specimen at a gradual rate. At higher curvatures the ripple growth accelerated, interacted with the roll, and then localized, which led to a limit-moment instability and the formation of a local buckle. The growth of the roll was accompanied by a rapid increase in torque. The interaction between the ripple and the roll depended in the length of the specimen. (Corona & Ellison, May 1997)

Lateral torsional buckling roll characteristics depended upon the ratio L/h of the specimen. When L/h = 20, LTB characteristics were present, however at L/h=10, no LTB roll characteristics were present. In these cases, the most severe feature of the ripple pattern initiated the local buckling mechanism. Further bending caused the web deformation and roll to grow concurrently at an accelerated rate, which eventually formed a local buckle. (Corona & Ellison, May 1997)

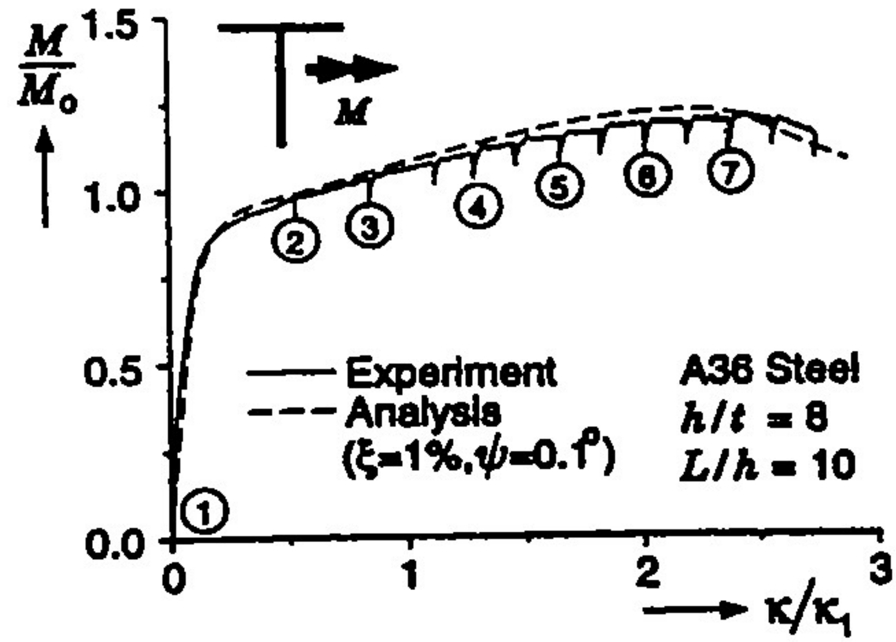
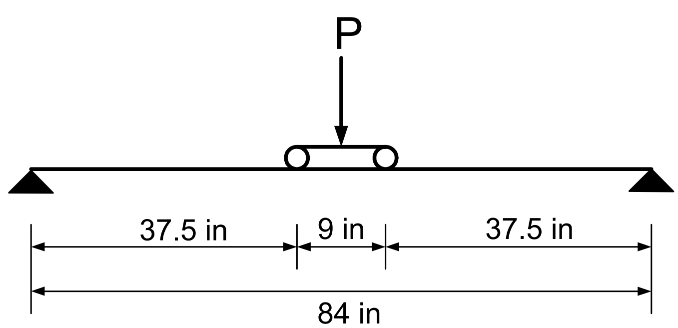


Figure 8 Typical Moment Curvature Response

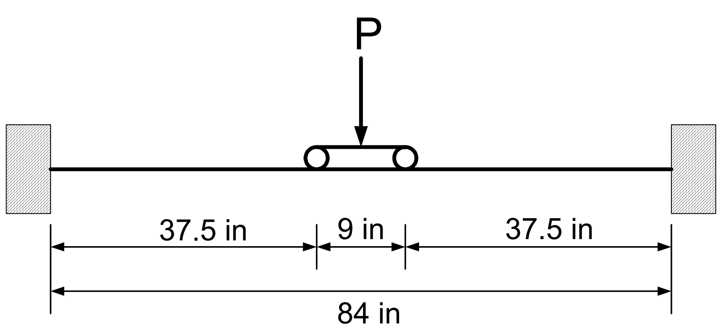
The predictions of the response of the beams agreed well with experimental measurements. Predictions for both the moment-curvature response and the cross section deformation parameter were consistent with experimental results for moderate curvatures. The finite element bifurcation analysis predicted the curvature at which the ripple appeared, which was in good agreement with experimental observations. (Corona & Ellison, May 1997)

Further experimental data has been gathered on the response of WTEE beams placed in both positive and negative flexure. In particular, Duane S. Ellifritt, Gregory Wine, Thomas Sputo, and Santosh Samuel explored the behavior of WTEE beams placed in both positive and negative flexure.

Specimens with a 7-foot span were loaded using a mechanically driven universal testing machine. The nominal sections used were WT5x13, WT6x13, and WT6x15. A load cell was used to measure loads, and deflections were measured using an LVDT. Five of the eight experiments performed were for positive bending, while the remaining three had the ends fixed creating negative bending at the supports, see figure 9.



Positive Bending Test



Negative Bending Test

Figure 9 Positive and Negative Bending Tests

Load versus deflection curves and moment versus deflection diagrams were developed from the experimental measurements of the positive bending tests. The deflections followed the predicted linear-elastic deflections quite well until the initiation of yielding in the stem at M_y, then the deflections became nonlinear; beginning to gradually increase until the plastic capacity of the section was reached.

The negative bending test sections failed in the region of negative bending where the stem was in flexural compression. The measured deflections generally followed the predicted elastic deflections once the slippage of the specimen in the supports was considered.

Ellifritt et al. used the results obtained from the experiments conducted to reevaluate the LRFD and ASD specifications. It is noted that the LRFD Equation F1-15 is the limiting lateral buckling equation for WTEE strength in both positive and negative bending. Ellifritt et al. state that in positive bending, it is impossible at practical beam lengths to develop this elastic strength before a plastic hinge is formed. It was observed that a WT6x20 will no experience lateral buckling with the flange in compression until the unbraced length reaches 75 feet. They continue on to observe that it would probably be better just to note the capacity in positive flexure to be $1.5M_y$ and to eliminate the use of Equation F1-15 for positive bending. Additionally, for negative bending, it was observed that for any case where the elastic buckling stress is greater than the yield stress, Equation F1-15 will not control. For cases where the elastic buckling stress is less than the yield stress, lateral buckling will govern for negative bending, and the lesser of M_y and Equation F1-15 should govern. (Ellifritt et al, 1992)

Similar results were recorded for the ASD specification. Ellifritt et al. state that it is unnecessarily conservative to limit the allowable bending stress in the stem for positive bending to $0.66F_y$. A limit of $0.9M_y$ would be more reasonable and in keeping with the LRFD design criteria; which allow a service load of $0.90F_y$ at a live/dead load ratio of 3/1. Negative bending of WTEEs is not covered in the ASD specification. It was recommended to check both lateral buckling and the strength for specific sections and lengths, for cases where the elastic buckling stress is less than the yield stress. (Ellifritt et al, 1992)

1.2 Scope

The main objective of the current study is to investigate the general response and governing limit states exhibited by WTEE beams at their maximum load. Compactness criteria that ensure attainment of R=3 are formulated through the use of experimentally verified nonlinear finite element modeling techniques. Parametric studies are conducted to determine the influence of various geometrical properties on the maximum allowable flexural capacity of WTEEs. The information obtained is used to make recommendations for changes to the current US steel building design specifications.

1.3 Thesis Organization

Section 2 provides an overview of the current provisions used for the design of a typical WTEE beam. Specific equations and limitations will be outlined in this section. The specific finite element modeling methods and techniques will be described in Section 3. Section 3.1 discusses the nonlinear finite element methods used to conduct this research along with an overview of the finite element modeling program ABAQUS. The finite element model that will be analyzed by ABAQUS for this research will be described in Section 4. Section 5 discusses, in detail, the parametric study conducted. The conclusions of this study will be provided in Section 6.

2.0 CURRENT DESIGN PROVISIONS FOR A WTEE

The nominal moment capacity for a WTEE loaded in flexure, such that bending occurs within the plane of the web, is governed by the specification provisions in Chapter F of the American Institute of Steel Construction Load and Resistance Factor Design Manual of Steel Construction (LRFD). This chapter applies to compact and noncompact doubly and singly symmetric prismatic members subject to flexure and shear. Because the current research focuses on flexural design, Section 1 of Chapter F, Design For Flexure, will be explored.

A section is said to be compact if it is capable of developing a fully plastic stress distribution and posses a rotation capacity of approximately three before the onset of local buckling (AISC LRFD, Second Edition). In order to prevent local or global buckling prior to the attainment of M_p, the beam must be compact and adequately braced (Salmon and Johnson, 1996).

To attain the requisite ductility for compactness, three limit states must be investigated to determine adequacy: lateral-torsional buckling (LTB), local buckling of the compression flange (FLB), and local buckling of the web (WLB). The nominal flexural strength M_n assumes the value is the lowest value obtained from consideration of these three limit states. These limit states depend, respectively, on the beam slenderness ratio L_b / r_y, the width-thickness ratio $b_f / 2t_f$ of the compression flange and the width-thickness ratio h / t_w of the web. For convenience, all three measures of slenderness are denoted by λ.

Chapter F, Section 1 states that for unbraced compact beams, noncompact tees and double angles, only the limit states of yielding and lateral-torsional buckling are applicable. It is noted that the limit states for local buckling are not applicable. Section 1 applies to homogeneous and hybrid shapes with at least one axis of symmetry and which are subject to simple bending about one principal axis. For simple bending, the beam is loaded in a plane parallel to a principal axis that passes through the shear center or the beam is restrained against twisting at load points and supports. Only the limit states of yielding and lateral-torsional buckling are considered in this section. Appendix F1 is applied for lateral-torsional buckling of other singly symmetric shapes and for the limit states of flange local buckling and web local buckling of noncompact or slender-element sections (AISC LRFD Second Edition).

Salmon and Johnson state that a T-section may be thought of as a monosymmetric I-shaped section that has the moment of inertia I_y of one flange equal to zero. Traditionally, both ASD and LRFD have been vague on how a T-section is to be treated. Rolled structural tees will rarely have strength controlled by the lateral-torsional buckling limit state. Whenever a tee section is loaded in the plane of its web (moment about the x-axis) and r_x is less than r_y, there is no limit on laterally unbraced length. Rolled tees are quite often subject to bending about the minor axis. Under this condition, the AISC LRFD-F1 states that the lateral torsional buckling limit state is not applicable (Salmon and Johnson, 1996).

Following this same reasoning, when a WTEE having its flange in compression is bent about its major axis and $r_x > r_y$, Equation F1-4 applies for L_p, the limiting laterally unbraced length for full plastic bending capacity:

$$L_p = \frac{300 r_y}{\sqrt{F_{yf}}} \tag{2-1}$$

From LRFD-Appendix Table A-F1.1, when L_b, the laterally unbraced length, does not exceed L_p, and λ, does not exceed the limiting slenderness parameter, λ_p, for the flange local buckling limit state, the yielding limit state controls. It may be expected that the plastic moment, M_p will be reached. However, when the shape factor, $\xi = Z_x / S_x$, is large, too much plastic deformation may occur at service load. The shape factor for WTEEs may be as high as 2.0. As a result of the foregoing, LRFD-F1.2c limits the nominal strength M_n (Salmon and Johnson, 1996):

1. For stem in compression,

$$M_n \leq 1.0 M_y \tag{2-2}$$

2. For stem in tension,

$$M_n \leq 1.5 M_y \tag{2-3}$$

When L_b exceeds L_r, the elastic lateral-torsional buckling limit state controls. Note that L_r is the value of L_b at which $M_{cr} = M_r$. According to LRFD-F1.2c, Equation F1-15,

$$M_{cr} = \frac{\pi \sqrt{E I_y G J}}{L_b} \left[B + \sqrt{1 + B^2} \right] \tag{2-4}$$

where

$$B = \pm 2.3\left(\frac{d}{L_b}\right)\sqrt{\frac{I_y}{J}} \tag{2-5}$$

The plus sign is for the stem in tension and the minus sign is used for the stem in compression: "If the tip of the stem is in compression anywhere along the unbraced length, use the negative value of B" (LRFD-F1.2c).

LRFD Table B5.1 lists the limiting width-thickness ratios for compression elements. For WTEES the width to thickness ratio is b/t. No limiting width-thickness ratio is given for compact stems of tees. For noncompact stems of tees,

$$\lambda_r = \frac{127}{\sqrt{F_y}} \tag{2-6}$$

For flanges of WTEEs, λ_p is given for compact members, and λ_r is given for noncompact members.

$$\lambda_p = \frac{65}{\sqrt{F_y}} \qquad \lambda_r = \frac{141}{\sqrt{F_y - 10}} \tag{2-7a \& b}$$

Values of λ_p for FLB and WLB produce a compact section with rotation capacity of about three, after reaching M_p, before the onset of local buckling, and therefore meet the requirements for plastic analysis of load effects. On the other hand, limiting value of λ for LTB does not allow for plastic analysis because it does not provide rotation capacity beyond that needed to develop M_p. As a result, the unbraced length in a compact section proportioned with plastic design techniques should not exceed that outlined by LRFD-F1-17:

$$L_{pd} = \frac{\left[3{,}600 + 2{,}200\left(M_1 / M_2\right)\right] r_y}{F_y} \tag{2-8}$$

2.1 Derivation of WTEE-LTB Equation

The derivation of the WTEE-LTB equation shown through the use of differential equations for a singly symmetric thin-walled open cross-section subjected to a concentrated moment loading follows from the development presented by Galambos (1972).

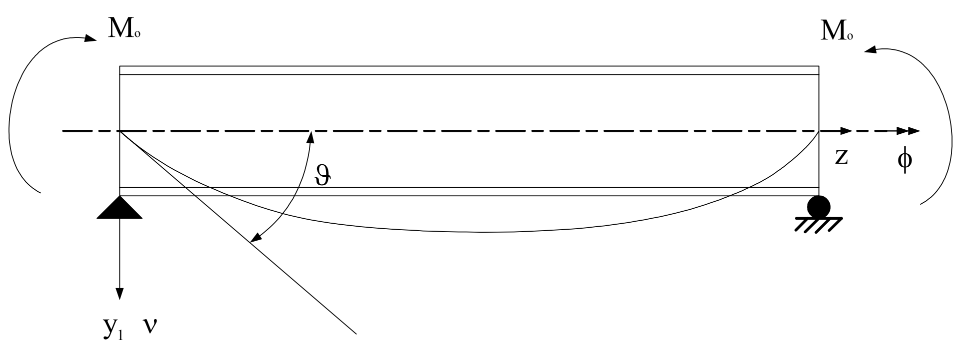


Figure 10 Concentrated Moment Loading on a Thin Walled Open Cross-Section

$$EIu^{IV} + M_x\phi'' + 2M_x'\phi' = 0 \tag{2-9}$$

$$EI_w\phi^{IV} - (GK_T + M_xB_x)\phi'' - M_xu'' = 0 \tag{2-10}$$

Let $M_x = M_o \Rightarrow M_x' = 0$

For a doubly symmetric cross-section,

$$\beta_x = \frac{1}{I_x}\int_{-y_1}^{y_1}\int_{-x_1}^{x_1} y(x^2 + y^2)dxdy = 0 \tag{2-11}$$

hence, the differential equations above will now take the form:

$$EI_yu^{IV} + M_o\phi'' = 0 \tag{2-12}$$

$$EI_w\phi^{IV} - GK_T\phi'' + M_ou'' = 0 \tag{2-13}$$

In the case of the singly symmetric beam, $\beta_x \neq 0$; hence, the differential equations become:

$$EI_yu^{IV} + M_o\phi'' = 0 \tag{2-14}$$

$$EI_w\phi^{IV} - (GK_T + M_o\beta_x)\phi'' + M_ou'' = 0 \tag{2-15}$$

Integrating the first of these two equations twice yields:

$$EI_y u''+M_o\phi + C_1 z + C_2 = 0 \tag{2-16}$$

Applying simple boundary conditions:

$$u(0)=u(L)=\phi(0)=\phi(L)=u''(0)=u''(L)=\phi''(0)=\phi''(L)=0 \tag{2-17}$$

at $z=0$,

$$EI_y u''(0)+M_o\phi(0)+C_1 0+C_2=0 \Rightarrow C_2=0 \tag{2-18}$$

at $z=L$,

$$EI_y u''(L)+M_o\phi(L)+C_1 L=0 \Rightarrow C_1=0 \tag{2-19}$$

thus, the first equation can be re-expressed as,

$$u''=-\frac{M_o\phi}{EI_y} \tag{2-20}$$

Using this result in the second differential equation (2-15) results in,

$$EI_w\phi^{IV} - (GK_T + M_o\beta_x)\phi'' + \frac{M_o^{\ 2}}{EI_y}\phi = 0 \qquad (2\text{-}21)$$

This may be re-expressed as:

$$\phi^{IV} - \lambda_1\phi'' + \phi = 0 \qquad (2\text{-}22)$$

where,

$$\lambda_1 = \frac{GK_T + M_o\beta_x}{EI_w} \qquad \& \qquad \lambda_2 = \frac{M_o^{\ 2}}{E^2 I_y I_w} \qquad (2\text{-}23 \ \& \ 24)$$

The solution of this type of differential equation has the form:

$$\phi = C_1 \cosh\alpha_1 z + C_2 \sinh\alpha_1 z + C_3 \sin\alpha_2 z + C_4 \cos\alpha_2 z \qquad (2\text{-}25)$$

$C_1, C_2, C_3, \& C_4$ are simply constants of integration while $\alpha_1 \ \& \ \alpha_2$ are:

$$\alpha_1 = \sqrt{\frac{\lambda_1 - \sqrt{\lambda_1^{\ 2} + 4\lambda_2}}{2}} \qquad \alpha_2 = \sqrt{\frac{-\lambda_1 + \sqrt{\lambda_1^{\ 2} + 4\lambda_2}}{2}} \qquad (2\text{-}26 \ \& \ 27)$$

Based on the torsional boundary conditions (i.e. no twisting at the ends and no warping restraint at the ends):

$$\phi(0) = \phi(L) = \phi''(0) = \phi''(L) = 0 \tag{2-28}$$

$$\phi = C_1 \cosh \alpha_1 z + C_2 \sinh \alpha_1 z + C_3 \sin \alpha_2 z + C_4 \cos \alpha_2 z \tag{2-29}$$

$$\phi' = C_1\alpha_1 \sinh \alpha_1 z + C_2\alpha_1 \cosh \alpha_1 z + C_3\alpha_2 \cos \alpha_2 z - C_4\alpha_2 \sin \alpha_2 z \tag{2-30}$$

$$\phi'' = C_1\alpha_1^2 \cosh \alpha_1 z + C_2\alpha_1^2 \sinh \alpha_1 z - C_3\alpha_2^2 \sin \alpha_2 z - C_4\alpha_2^2 \cos \alpha_2 z \tag{2-31}$$

Applying the boundary conditions:

$$\phi(0) = C_1(1) + C_2(0) + C_3(0) + C_4(1) \tag{2-32}$$

$$\phi''(0) = C_1\alpha_1^2(1) + C_2\alpha_1^2(0) + C_3\alpha_2^2(0) + C_4(-\alpha_2^2) \tag{2-33}$$

$$\phi(L) = C_1 \cosh \alpha_1 L + C_2 \sinh \alpha_1 L + C_3 \sin \alpha_2 L + C_4 \cos \alpha_2 L \tag{2-34}$$

$$\phi''(L) = C_1\alpha_1^2 \cosh \alpha_1 L + C_2\alpha_1^2 \sinh \alpha_1 L - C_3\alpha_2^2 \sin \alpha_2 L - C_4\alpha_2^2 \cos \alpha_2 L \tag{2-35}$$

These four boundary equations may be expressed in matrix form:

$$\begin{bmatrix} 1 & 0 & 0 & 1 \\ \alpha_1^2 & 0 & 0 & -\alpha_2^2 \\ \cosh\alpha_1 L & \sinh\alpha_1 L & \sin\alpha_2 L & \cos\alpha_2 L \\ \alpha_1^2\cosh\alpha_1 L & \alpha_1^2\sinh\alpha_1 L & -\alpha_1^2\sin\alpha_2 L & -\alpha_2^2\cos\alpha_2 L \end{bmatrix} \begin{Bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix} \qquad \text{(2-36)}$$

The trivial solution is that $C_1 = C_2 = C_3 = C_4 = 0$. The non-trivial solution requires that the determinant of the coefficient matrix must vanish. Using Cramer's rule, we get (2-37):

$$\begin{vmatrix} 0 & 0 & -\alpha_2^2 \\ \sinh\alpha_1 L & \sin\alpha_2 L & \cos\alpha_2 L \\ \alpha_1^2\sinh\alpha_1 L & -\alpha_2^2\sin\alpha_2 L & -\alpha_2^2\cos\alpha_2 L \end{vmatrix} - \begin{vmatrix} \alpha_1^2 & 0 & 0 \\ \cosh\alpha_1 L & \sinh\alpha_1 L & \sin\alpha_2 L \\ \alpha_1^2\cosh\alpha_1 L & \alpha_1^2\sinh\alpha_1 L & -\alpha_2^2\sin\alpha_2 L \end{vmatrix} =$$

$$(0)\begin{vmatrix} \sin\alpha_2 L & \cos\alpha_2 L \\ -\alpha_2^2\sin\alpha_2 L & -\alpha_2^2\cos\alpha_2 L \end{vmatrix} - (0)\begin{vmatrix} \sinh\alpha_1 L & \cos\alpha_2 L \\ \alpha_1^2\sinh\alpha_1 L & -\alpha_2^2\cos\alpha_2 L \end{vmatrix}$$

$$-\alpha_2^2\begin{vmatrix} \sinh\alpha_1 L & \sin\alpha_2 L \\ \alpha_1^2\sinh\alpha_1 L & -\alpha_2^2\sin\alpha_2 L \end{vmatrix} - \left\{\alpha_1^2\begin{vmatrix} \sinh\alpha_1 L & \sin\alpha_2 L \\ \alpha_1^2\sinh\alpha_1 L & -\alpha_2^2\sin\alpha_2 L \end{vmatrix}\right.$$

$$\left. -(0)\begin{vmatrix} \cosh\alpha_1 L & \sin\alpha_2 L \\ \alpha_1^2\cosh\alpha_1 L & -\alpha_2^2\sin\alpha_2 L \end{vmatrix} + (0)\begin{vmatrix} \cosh\alpha_1 L & \sinh\alpha_1 L \\ \alpha_1^2\cosh\alpha_1 L & \alpha_1^2\sinh\alpha_1 L \end{vmatrix}\right\} = 0$$

Simplifying,

$$\begin{aligned} &-\alpha_2^2\left[-\sinh\alpha_1 L\alpha_2^2\sin\alpha_2 L - \alpha_1^2\sinh\alpha_1 L\sin\alpha_2 L\right] \\ &-\alpha_1^2\left[-\sinh\alpha_1 L\alpha_2^2\sin\alpha_2\sin\alpha_2 L - \alpha_1^2\sinh\alpha_1 L\sin\alpha_2 L\right] = 0 \end{aligned} \qquad \text{(2-38)}$$

Expanding and collecting terms,

$$(\alpha_2{}^2 + \alpha_1{}^2)^2 \sin\alpha_2 L \sinh\alpha_1 L = 0 \tag{2-39}$$

Because $(\alpha_2{}^2 + \alpha_1{}^2)^2 > 0$

$$\sinh\alpha_1 L \sin\alpha_2 L = 0 \tag{2-40}$$

$\sinh\alpha_1 L = 0$ only when $\alpha_1 = 0$, this is the trivial case. Thus, the critical condition is:

$$\sin\alpha_2 L = 0 \tag{2-41}$$

which can only be true when:

$$\alpha_2 L = n\pi \tag{2-42}$$

Thus, for the lowest energy state,

$$\sqrt{\frac{-\lambda_1 + \sqrt{\lambda_1{}^2 + 4\lambda_2}}{2}}L = \pi \tag{2-43}$$

$$\sqrt{\frac{\dfrac{-GK_T - M_o\beta_x}{EI_w} + \sqrt{\left(\dfrac{GK_T + M_o\beta_x}{EI_w}\right)^2 + \dfrac{4M_o^{\ 2}}{E^2 I_y I_w}}}{2}}(L) = \pi \qquad (2\text{-}44)$$

Expanding, we get (2-45):

$$\frac{1}{2}\left[-\frac{GK_T}{EI_w} - \frac{M_o\beta_x}{EI_w} + \left\{\left(\frac{GK_T}{EI_w}\right)^2 + 2\frac{GK_T M_o\beta_x}{E^2 I_w^{\ 2}} + \left(\frac{M_o\beta_x}{EI_w}\right)^2 + \frac{4M_o^{\ 2}}{E^2 I_y I_w}\right\}^{\frac{1}{2}}\right]L^2 = \pi^2$$

Re-arranging terms:

$$\left(\frac{2\pi^2}{L^2} + \frac{GK_T}{EI_w} + \frac{M_o\beta_x}{EI_w}\right)^2 = \left(\frac{GK_T}{EI_w}\right)^2 + 2\frac{GK_T M_o\beta_x}{E^2 I_w^{\ 2}} + \left(\frac{M_o\beta_x}{EI_w}\right)^2 + \frac{4M_o^{\ 2}}{E^2 I_y I_w} \qquad (2\text{-}46)$$

After squaring, the left-hand side becomes:

$$\frac{4\pi^4}{L^4} + \left(\frac{GK_T}{EI_w}\right)^2 + \left(\frac{M_o\beta_x}{EI_w}\right)^2 + \frac{4\pi^2 GK_T}{L^2 EI_w} + \frac{4\pi^2 M_o\beta_x}{L^2 EI_w} + 2\frac{M_o\beta_x GK_T}{E^2 I_w^{\ 2}} \qquad (2\text{-}47)$$

Substituting back into the original equation and canceling terms:

$$\frac{4\pi^4}{L^4} + \frac{4\pi^2 GK_T}{L^2 EI_w} + \frac{4\pi^2 M_o\beta_x}{L^2 EI_w} = \frac{4M_o^{\ 2}}{E^2 I_y I_w} \qquad (2\text{-}48)$$

This may be re-expressed as:

$$\left(\frac{4}{E^2 I_y I_w}\right)M_o^{\ 2} - \left(\frac{4\pi^2\beta_x}{L^2 EI_w}\right)M_o - \left(\frac{4\pi^2 GK_T}{L^2 EI_w} + \frac{4\pi^4}{L^4}\right) = 0 \qquad (2\text{-}49)$$

Using the quadratic equation, solve for M_0, the elastic critical moment:

$$M_o = \frac{\pi^2 E\beta_x I_y}{2L^2}\left\{1 \pm \sqrt{1 + \frac{4}{\beta_x^{\ 2}}\left(\frac{L^2 GK_T}{\pi^2 EI_y} + \frac{I_w}{I_y}\right)}\right\} \qquad (2\text{-}50)$$

For the WTEE shown below:

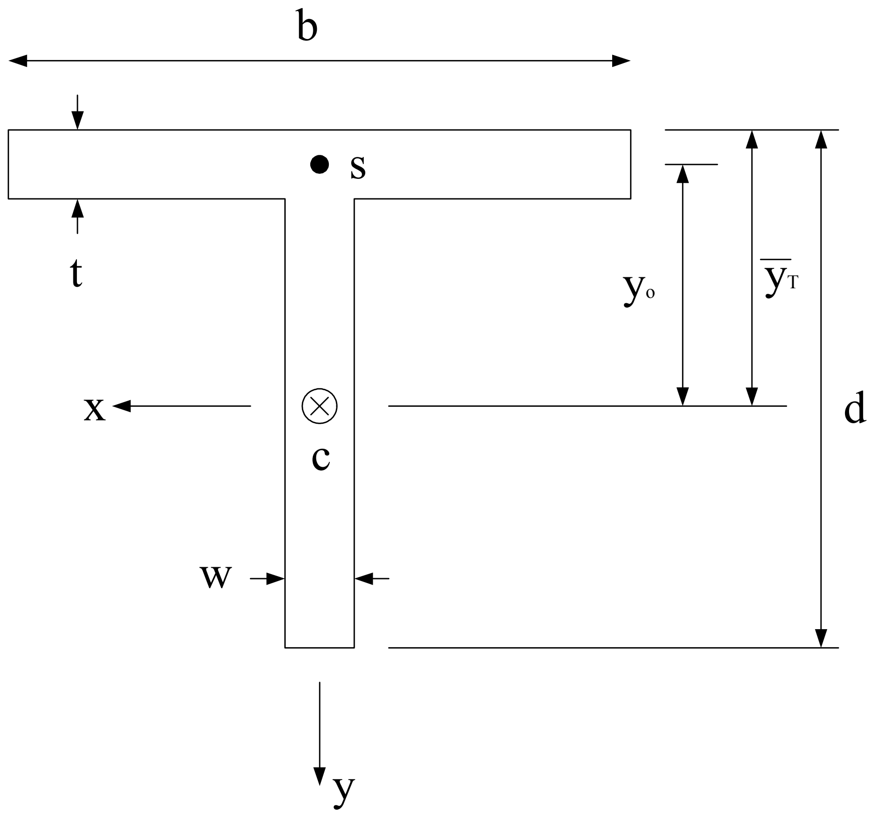


Figure 11 WTEE Dimensions

$$\beta_x = \frac{1}{I_x}\left\{\frac{w}{4}\left[(d-\bar{y}_T)^4-(\bar{y}_T-t)^4\right]-bt\left(\bar{y}_T-\frac{t}{2}\right)\left[\frac{b^2}{12}+\left(\bar{y}_T-\frac{t}{2}\right)^2\right]\right\}-2y_o \qquad (2\text{-}51)$$

Shown below is the elastic buckling comparison between LRFD (F1-15) and the "exact" solution.

Exact Solution:

$$M_o = \frac{\pi^2 E \beta_x I_y}{2L_b^{\,2}} \left\{ 1 \pm \sqrt{1 + \frac{4}{\beta_x^{\,2}} \left(\frac{L_b^{\,2} GJ}{\pi^2 E I_y} + \frac{C_w}{I_y} \right)} \right\} \tag{2-52}$$

where:

$$\beta_x = \frac{1}{I_x} \left\{ \frac{t_w}{4} \left[(d-y)^4 - (y-t_f)^4 \right] - b_f t_f \left(y - \frac{t_f}{2} \right) \left[\frac{b_f^{\,2}}{12} + \left(y - \frac{t_f}{2} \right)^2 \right] \right\} \tag{2-53}$$

AISC LRFD (F1-15):

$$M_{cr} = \frac{\pi \sqrt{E I_y G J}}{L_b} \left[B + \sqrt{1 + B^2} \right] \tag{2-54}$$

where:

$$B = \pm 2.3 \left(\frac{d}{L_b} \right) \sqrt{\frac{I_y}{J}} \tag{2-55}$$

In both cases above, the positive radical means flange in compression.

3.0 FINITE ELEMENT ANALYSIS

The objective of the current study is to observe the behavior of WTEE beams at ultimate when subjected to bending loads. In order to attain this, it is necessary to determine the cross-section's plastic moment capacity and to observe the ability of the beam to maintain capacity through sufficient member plastic rotations as required for the formation of a collapse mechanism. Success in this regard can be gauged through the use of a load versus deformations plots for the WTEE beams studied. Specifically, a plot of the beam's moment versus rotation response is tracked as shown in Figure 2. A nonlinear displacement based finite element analysis is performed to obtain this plot.

Nonlinear techniques are used because it is expected that the beam will display nonlinear behavior prior to reaching its ultimate capacity. There are two important types of nonlinearities within structural engineering: material and geometric nonlinearities. The first of these relates to the element material properties themselves and how they vary with the deformation of the elements. (i.e. these occur as a result of a nonlinear stress-strain relationship). The second type of a general nonlinearity occurs when the geometric configuration of the assemblage changes sufficiently under load to influence the equilibrium relationships of the structure. This is generally known as geometric nonlinearity.

The commercial multipurpose finite element software package ABAQUS is employed in this research. ABAQUS has the ability to treat both geometric and material nonlinearities that may arise in the model.

The finite element method is powerful when used to solve complex problems. By definition, the method is a generalization of standard structural analysis procedures, which permits the calculation of stresses and deflections in two- and three-dimensional structures by the same techniques that are applied in the analysis of ordinary framed structures. The finite element method was named based on the fact that, to begin the process of analysis, the structure must be discretized into a finite number of elements, which are interconnected at a finite number of nodal points.

In our case, the WTEE beam is discretized into a system of small bodies, or finite elements. Nodal points, or nodes, then interconnect these elements at points shared by two or more elements. The assembly process results in a system of simultaneous algebraic equations that are solved to obtain the unknown nodal values of the problem. In our case, the unknowns are displacements. These results are then combined to form a solution for the overall member. It is necessary to select elements that are compatible in deformation with adjacent elements. If this property were not satisfied then the elements would deform independently from one another and gaps or overlaps would develop along the edges of the elements; thus causing the idealization to be much more flexible than the actual system.

The final solution for the WTEE beam is generalized as the determination of the displacements at each node, and the stresses within each element, all combined to make up the entire body. The body is therefore discretized into many small elements, and an analysis is performed to arrive at all of the subsequent unknown displacements and stresses.

3.1 Nonlinear Finite Element Analysis

Non-linear analysis is used to iteratively determine the state of equilibrium of the structure subjected to an applied loading. Using this method, the solution cannot be determined from a system of linear equations. Rather, the load is specified as a function of “time”. The “time” is then broken down into intervals that are incrementally applied in small steps so as to trace the non-linear equilibrium response. The values of the accumulated “time” represent Load Proportionality Factors (LPF) related to the evolution of the load history.

In the incremental analysis technique, each step is assumed to be linear with the loading or displacement applied in a series of increments. Each time a new displacement increment is computed, the result is added to the previous displacement of the structural configuration. This configuration is computed for each incremental step. It is these increments in displacement that allow for the observation of changes in the overall model configuration.

The tangent stiffness matrix of the model is used as a means of relating the changes in loads and the changes in displacements in a linearized fashion within an individual load increment (i.e. between two different LPFs). The internal loads and the deformation of the structure at the beginning of the increment are used to compute this stiffness matrix. The tangent stiffness matrix is commonly represented as:

$$[k_T] = [k_o] + [k_p] \tag{3-1}$$

where $\left[k_o\right]$ is the conventional linear stiffness matrix for uncoupled bending and axial behavior and $\left\lfloor k_p \right\rfloor$ is the initial stiffness matrix, dependent upon the axial force at the beginning of each load increment.

3.1.1 Nonlinear Equilibrium Equations

The principal of virtual work is the concept whereupon a deformable body in equilibrium is subjected to an arbitrary virtual displacement and reacts with a compatible deformation. It is said that the virtual work of the external forces are equal to the virtual strain energy of the internal stresses. Otherwise stated as:

$$\delta U^{(e)} = \delta V^{(e)} \tag{3-2}$$

where $\delta U^{(e)}$ is the virtual strain energy due to internal stresses, and $\delta V^{(e)}$ is the virtual work of external forces on the element. The external work is due to nodal, surface, and body forces moving through virtual displacements.

The virtual work statement of equilibrium is at the heart of the finite element method in that it is used directly for the formulation for the equilibrium equations used within each increment of the nonlinear analysis.

3.1.2 Nonlinear Finite Element Solution Techniques

In the current study, it is necessary to track the non-linear equilibrium path of the WTEE shape as the load is incrementally applied. The solution to (3-2) must be found using nonlinear finite element solution techniques.

There are several incremental solution techniques, however the two most commonly used are the Newton-Raphson technique, and the Riks-Wempner method. The Newton-Raphson solver is used to approximate a given function in each iteration by a quadratic function, see Figure 12. ABAQUS generally uses Newton's method as a numerical technique for solving the nonlinear equilibrium equations. The motivation for this choice is primarily the convergence rate obtained by using Newton's method compared to the convergence rates exhibited by alternate methods. The number of iterations needed to find a converged solution for a time increment will vary depending on the degree of non-linearity in the system. However, this method is unable to negotiate limit and bifurcation points and hence is not suitable to plot the unloading portion of a nonlinear equilibrium path and is therefore inadequate for this study (Earls, 1995). Alternatively, the Riks-Wempner method is an arc-length method generally used to solve post-buckling problems.

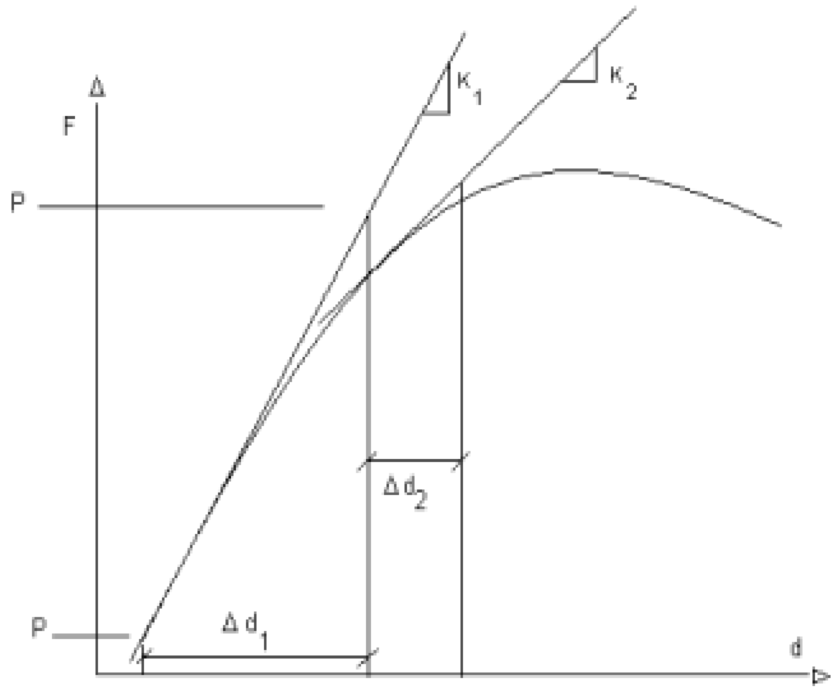


Figure 12 Schematic of Newton Raphson Solution Method

The incremental technique that will be implemented for the current study is the Riks-Wempner method provided by the ABAQUS program. The Riks-Wempner method allows for the equilibrium path to be traced into the unloading portion of the beam response. This method also provides some of the most efficient use of the computational resources during the nonlinear response since step size in an increment is tied to the convergence rate from the previous increment.

3.1.3 Riks-Wempner Method

The Riks method is generally used to predict unstable, geometrically nonlinear collapse of a structure. To analyze a post-buckling problem, it must be turned into a problem with continuous response instead of bifurcation. This effect can be accomplished by introducing an initial imperfection into a “perfect” geometry so that there is some response in the buckling mode before the critical load is reached.

Within ABAQUS there are three ways to define an imperfection. The first is as a linear superposition of buckling eigenmodes. The second is from the displacements of a static analysis. The last method to define an imperfection is by specifying the node number and imperfection values directly on the data lines while creating the input file for ABAQUS.

Unless the precise shape of an imperfection is known, an imperfection consisting of multiple superimposed buckling modes can be introduced. The usual approach involves two analysis runs with the same model definition. The first run performs an eigenvalue buckling analysis on the “perfect” structure to establish probable collapse modes and to verify that the mesh discretizes those modes accurately. The second analysis run will introduce an imperfection in the geometry by adding these buckling modes to the “perfect” geometry by using the IMPERFECTION card in the input file. The lowest buckling modes are assumed to provide the critical imperfections, so usually these are scaled and added to the “perfect” geometry to create the perturbed mesh. The imperfection thus has the form:

$$\Delta x_i = \sum_{i=1}^{m} \omega_i \phi_i \tag{3-3}$$

where ϕ_i is the ith mode shape and ω_i is the associated scale factor. ABAQUS then performs a geometrically nonlinear load-displacement analysis of the structure containing the imperfection using the Riks-Wempner method.

In simple cases, linear eigenvalue analysis may be sufficient for design evaluation; but if there is concern about material nonlinearity, geometric nonlinearity prior to buckling, or unstable postbuckling response, a load-deflection, or Riks, analysis must be performed to investigate the problem further. (ABAQUS, 1999)

The load magnitude is used as an additional unknown in the Riks method. The loads and displacements are solved for simultaneously. For this reason, another quantity must be used to measure the progress of the solution. ABAQUS uses the arc length along the static equilibrium path in load-displacement space. This approach provides solutions regardless of whether the response is stable or unstable.

As previously mentioned, when the nonlinear static equilibrium solution for unstable problems is desired, ABAQUS uses the Riks-Wempner method. In such cases, ABAQUS allows the effective solution to be determined for situations in which the load and/or the displacement may decrease as the solution evolves. This typical unstable static response is illustrated in Figure 13.

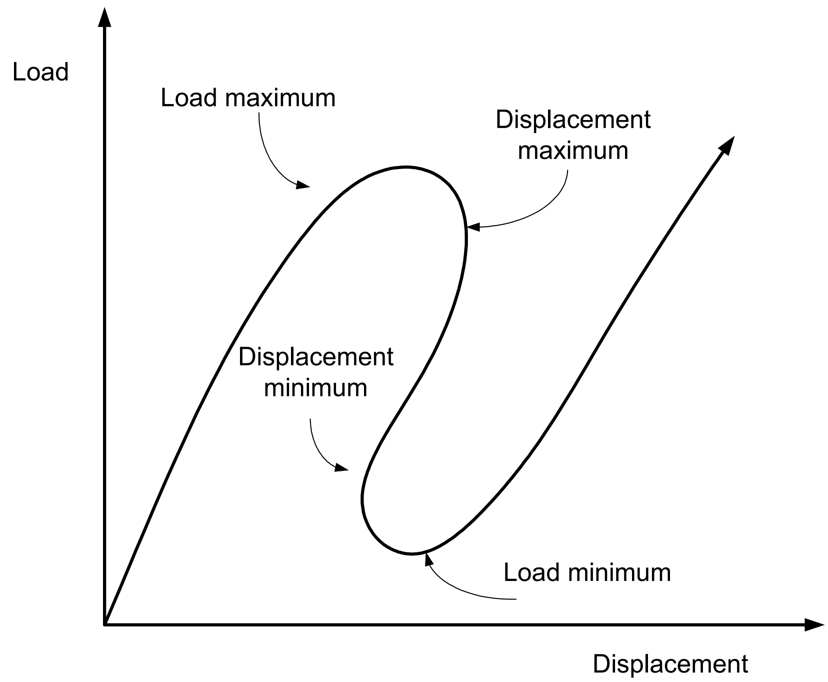


Figure 13 Typical Unstable Static Response

In the modified Riks method, it is assumed that all load magnitudes vary with a single scalar parameter; the loading is proportional to this parameter. The response is additionally assumed to be reasonable smooth and that sudden bifurcations do not occur. The essence of the method is that the solution is viewed as the discovery of a single equilibrium path in a space defined by the nodal variables and the loading parameter. Tracing this path as far as required allows the development of the solution. It is essential to limit the increment size due to the fact that many of the materials, and possibly loadings of interest will have path-dependent response. The increment size for the modified Riks algorithm is limited by moving a given distance along the tangent line to the current solution point and then searching for equilibrium in the plane that passes through the point thus obtained and that is orthogonal to the same tangent line. See Figure 14 for an illustration of the method.

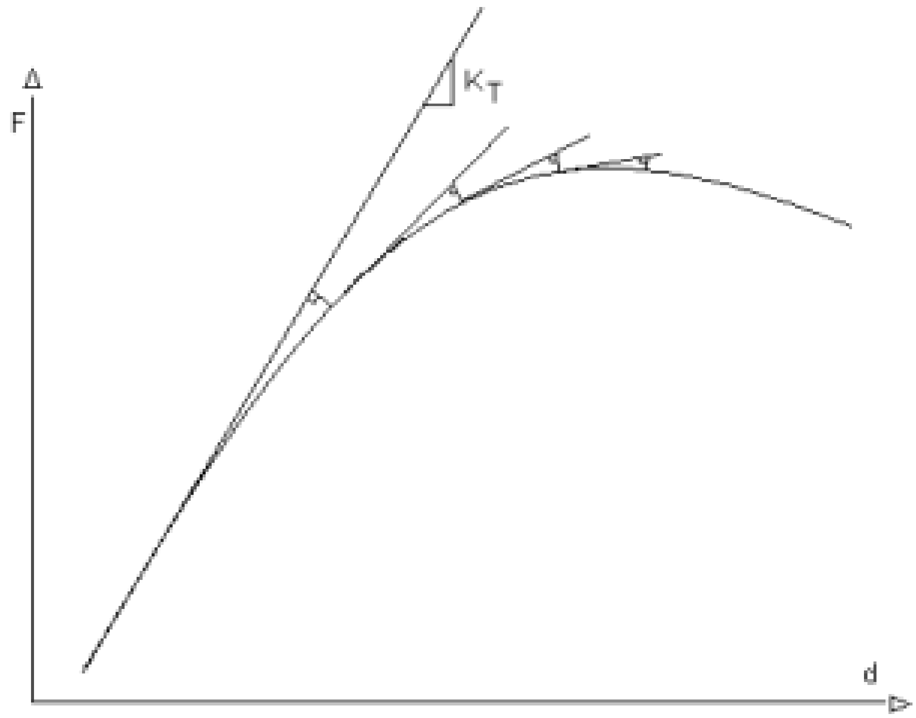


Figure 14 Schematic of Riks-Wempner solution Method

3.2 Element Selection

Shell elements were selected for use in the current study as a result of their ability to model structures in which one dimension, the thickness, is significantly smaller than the other dimensions and the stresses normal to the thickness direction are negligible. The nonlinear shell element used in the current research is the S9R5 (ABAQUS 1999). The naming of the elements is broken down into four categories. The first letter of the name denotes the element family, the second variable is the number of nodes used to define the element, the third is the type of integration employed in the formulation of the element stiffness matrix, and finally, the last variable in the element name is the number of nodal degrees of freedom. Using this nomenclature, the S9R5 is a shell element consisting of nine nodes using reduced integration, with 5 degrees of freedom per node. The order of numbering the nodes is illustrated in Figure 15.

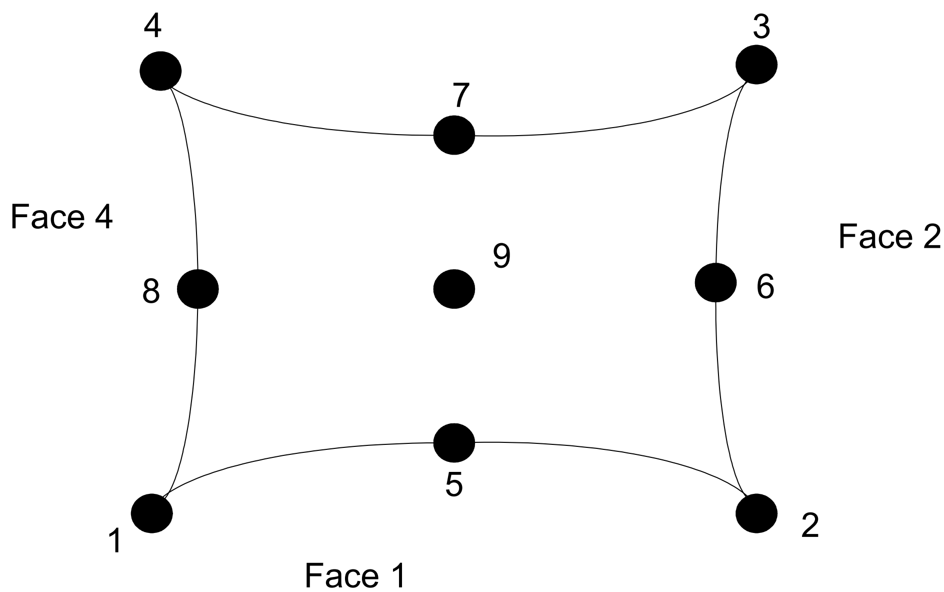


Figure 15 Order of Numbering for a 9-Node Element

4.0 FINITE ELEMENT MODEL

The current study involves a numerical investigation of the effects of systematically altering the dimensions of a WTEE beam. The WTEE beams are analyzed through the use of the commercial finite element software package ABAQUS. This section will describe in detail the ABAQUS models used for the parametric studies outlined in Section 5.0.

In the current research, WTEE beams are discretized into a number of nodes and shell elements. The actual number of elements and nodes is dependent upon the beam dimensions. A constant moment loading is achieved by applying a line load across the flange width at location corresponding to the mid-span of the simply supported beam configuration.

4.1 Geometry of Finite Element Model

The numerical model used is a representation of a simply supported singly symmetric prismatic WTEE beam subjected to a load at the midspan, which produces a constant moment. The only dimension that remains constant throughout the entirety the present parametric study is the depth of the beam. Other dimensions of the beam are varied in order to view the effects of the slenderness ratios, height of the beam to the thickness of the web, h/t_w, and the width of the flange to depth of beam, b/d on the structural ductility of fully braced WTEE beams subjected to constant moment loading. The actual dimensions will be discussed in detail in Section 5.

The distance between the two supports, L, is split into three equal lengths. The two end lengths are assigned properties that essentially make them behave as rigid ends. In order to accomplish this, the modulus of elasticity, E, in the shell elements comprising the ends is increased to be 10 times that of ordinary steel. It is at the junctions of the rigid steel and the flexible middle section that the concentrated loads are applied though the imposition of a series of nodal loads applied along a line parallel to the flange width. In addition, at this location, the stem is constrained against out of plane translation. The AISC LRFD Equation F1-17 is employed to determine the length of each section in order that the effects of lateral-torsional buckling may be avoided within the context of the present study. For singly symmetric I-shaped members with the compression flange equal to or larger than the tension flange loaded in the plane of the web, the unbraced length for design by plastic analysis is defined as (AISC LRFD Third Edition):

$$L_{pd} = 0.12 + 0.076\left(\frac{M_1}{M_2}\right)\left(\frac{E}{F_y}\right)r_y \tag{4-1}$$

Where:

$$\frac{M_1}{M_2} = -1.0 \tag{4-2}$$

The boundary conditions defined for the WTEE beams considered are representative of a simply supported beam. The flange is pinned along the top flange on one side, meaning that movement is restricted along the x, y, and z-axes. The other end of the flange has boundary conditions simulating a roller, i.e. movement along the y and z-axes is restricted. The only additional boundary conditions imposed upon the WTEE beam are those restricting out of plane bending at the junction of the rigid ends and the elastic portion of the beam.

The loads imposed on the beam are applied in the positive z direction. A unit load is applied to each node along the flange width at the rigid-elastic junction of the beam. The reader is referred to Figure 16 for clarification of the boundary conditions, applied loading and definition of the axes.

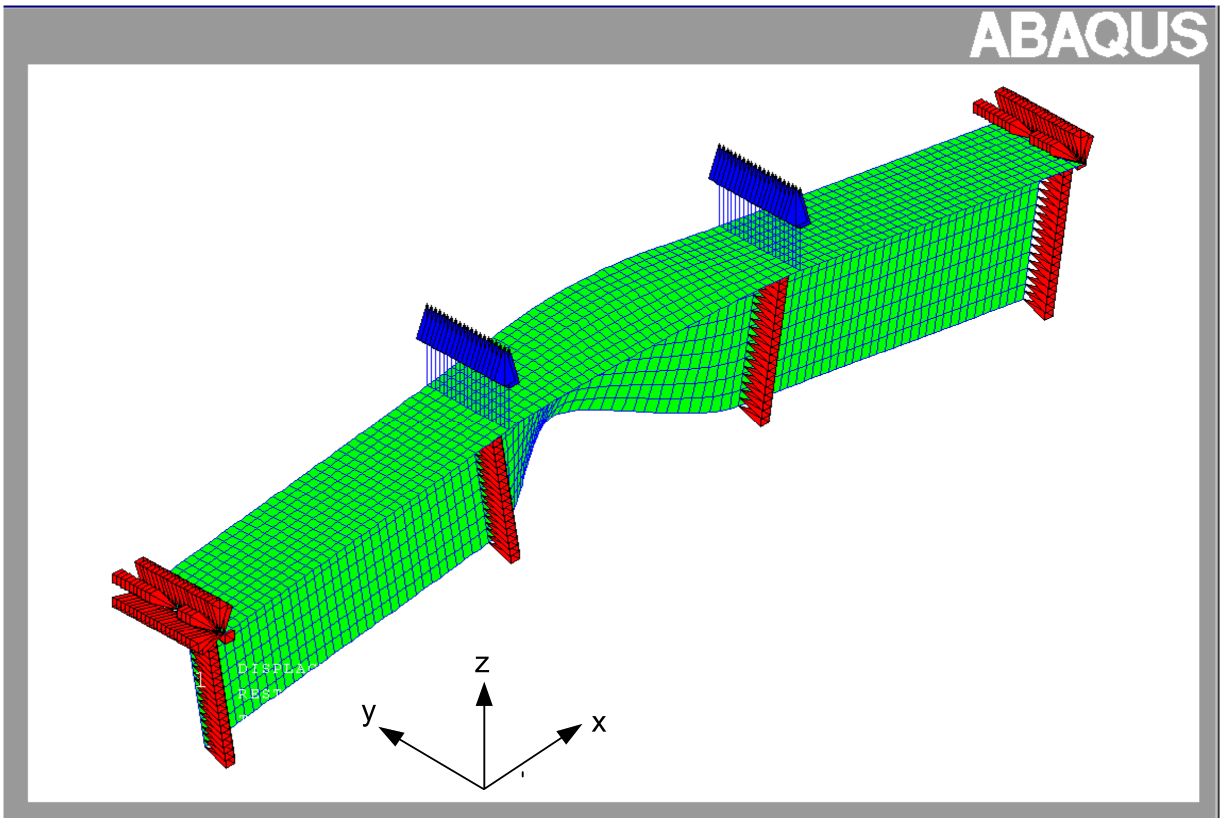


Figure 16 WTEE Beam Model

4.2 Finite Element Mesh

The WTEE beam numerical model constructed for this study is built from a dense finite element mesh of the ABAQUS S9R5 shell element described in Section 3.2. The mesh size is selected in order to maximize accuracy, while maintaining a reasonable computation time. A relationship exists between these two parameters; as accuracy of the model is increased through the introduction of more elements, the time required for ABAQUS to analyze the model is also increased. Figure 17 is an illustration of the mesh surface planes.

An aspect ratio of 1 was maintained for each of the elements of the WTEE beam model. That is, the sides of each of the elements are the same length. The planes of the mesh surfaces correspond with the middle surfaces of the constituent cross-sectional plate components of the beam as shown in Figure 17.

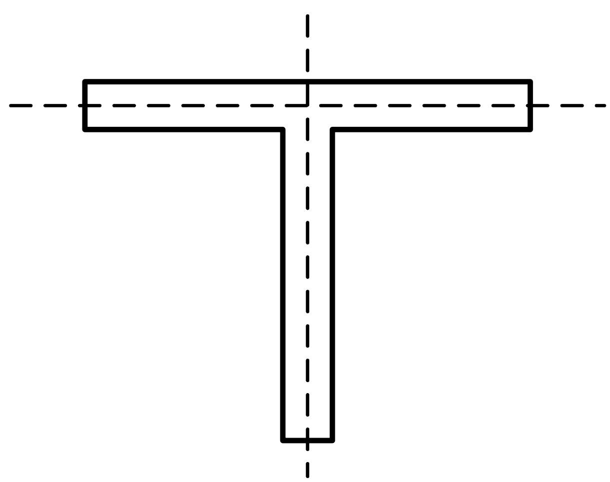


Figure 17 Mesh Surface Planes

Each of the cross-sectional plates is comprised of a node set. These node sets are then used to form an element set. Each element set may have its own properties. This allows for each of the plates to have a different thickness, which is imperative in the parametric studies considered herein. When the thickness of the flange, t_f, is altered, the height, h, of the WTEE is modified accordingly. The overall depth of the WTEE remains constant, however the height of the stem will vary due to the thickness of the flange.

The fact that the elements of the flange and stem are the same allows the two plate components to be compatible. This means that the stem mesh can be integrated with flange mesh through the use of an element set along the longitudinal centerline of the flange.

4.3 Imperfection Seed

In modeling studies where inelastic buckling is investigated, it is important that the evolution of the modeling solution be carefully monitored so that any indication of bifurcation in the equilibrium path is carefully assessed in order to try and ensure that the equilibrium branch being followed corresponds to the lowest energy state of the system (Earls and Shaw, 2001). Seeding the finite element mesh with an initial displacement field helps to ensure that the lowest energy path will be taken. The initial displacement is determined by using a linearized eigenvalue buckling analysis. From this analysis, an approximation to the critical buckling mode of the beam is obtained. In the current analysis, it was necessary to view each of the initial buckling modes determined by ABAQUS. Multiple buckling modes were produced for each imperfection study. However, the first buckling mode was not always the correct mode to use. It was necessary to look at each of the files and select an initial buckling mode that caused the stem to have a slight buckle produced. It was common for the shorter length beams to have a first buckling mode in which the flange buckled first. The desired displacement field obtained from the linearized eigenvalue buckling analysis is then superimposed on the finite element model as a seed imperfection. This imperfection is scaled so that the maximum initial displacement anywhere in the mesh is equal to one-one-thousandth of the unbraced length determined from the AISC LRFD Equation F1-17, (L_b/1000). Upon imposition of the initial displacement field, a full, nonlinear finite element analysis can be carried out in order to observe subsequent WTEE flexural ductility.

4.4 Material Property Definitions

A homogeneous WTEE beam is used for this study, meaning that the same steel properties are used for each of the plates making up the WTEE section. The section is made up of 50 ksi steel. ABAQUS requires that material properties for finite-strain calculations be given in terms of true stress (force per current area) and logarithmic strain. The true stress (σ_{true}) and logarithmic plastic strain $(\sigma_{\ln}^{pl})$ are expressed in terms of engineering stress and strain, respectfully as:

$$\sigma_{true} = \sigma_{eng}(1+\varepsilon_{eng}) \tag{4-3}$$

$$\varepsilon_{\ln}^{pl} = \ln(1+\varepsilon_{eng}) - \frac{\sigma_{true}}{E} \tag{4-4}$$

The input file for the study contains both elastic and plastic section properties for the beam. The elastic properties consist of the modulus of elasticity, E, and poisson's ratio, ν. For the current study, the modulus of elasticity is equal to 29000 ksi for the center length of the beam and 290000 ksi for the rigid ends, and poisson's ratio is kept constant at 0.3 for the entire length of the specimen. The plastic properties are given as points along the true stress versus true strain (logarithmic strain) curve as shown in Figure 18. ABAQUS uses these uniaxial material properties to extrapolate a yield surface in three-dimensional principal stress space using the von Mises yield criterion.

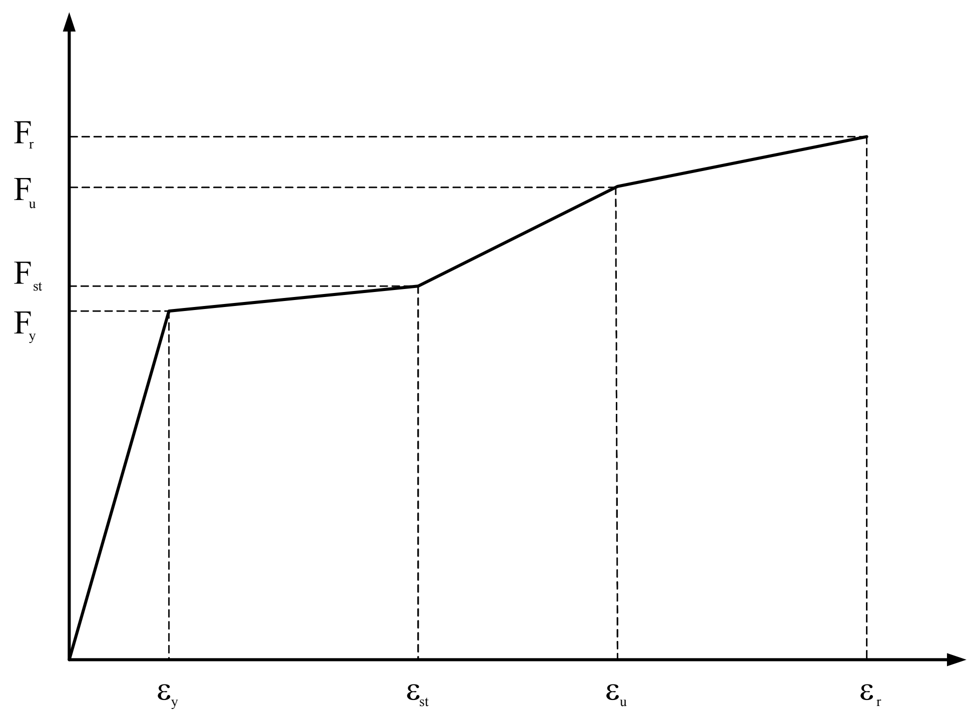


Figure 18 True Stress versus True Strain (Logarithmic Strain)

5.0 PARAMETRIC STUDIES AND RESULTS

The numerical model of Section 4 is used throughout the current parametric studies. The goal of this parametric study is to determine any correlations between the cross-sectional dimensions of the WTEE beam and its subsequent flexural ductility under the action of a constant moment loading.

The WTEE beam is put into negative flexure (stem in compression) by subjecting the beam to a constant moment through the application of a line load across the width of the flange at the one-third points of the beam, as illustrated in Figure 16.

The cross-sectional parameters varied in the present investigation are: the ratio b_f / d ; the flange slenderness ratio, $b_f / 2t_f$; and the web slenderness ratio, h/t_w. The results from the study of various parametric combinations involving the foregoing are studied in order that conclusions with regards to the relationships between the cross-sectional dimensions of the beams and the flexural ductility of the beam may be identified.

5.1 Parametric Studies

Eight different b_f / d ratios are explored, (1) 2.0, (2) 1.8, (3) 1.6, (4) 1.4, (5) 1.2, (6) 1.0, (7) 0.8, and (8) 0.6. To begin, the thickness of the flange is defined using the AISC LRFD provisions of Table B5.1, "Limiting Width-Thickness Ratios for Compression Elements". This was done in order to define the thickness of the flange required to produce a compact section (as if the flange of the WTEE were in flexural compression). The value of λ_p, the requirement for a compact width-thickness ratio, is taken to be the case of I-shaped rolled beams and channels in flexure. This can be expressed as:

$$\lambda_p = \frac{65}{\sqrt{F_y}} \tag{5-1}$$

To fulfill the slenderness equation,

$$\frac{b_f}{2t_f} = \lambda_p \tag{5-2}$$

With the depth, d, held constant at 14", the width to depth ratio, b_f / d, was used to define the width of the flange, b_f. This dimension was then used in the width to thickness ratio of equation (5-2) to determine the thickness of the flange, t_f. As stated in Section 4, the length of the beam was made to be three times the unbraced length, L_{pd}, as defined in Chapter F of the AISC LRFD.

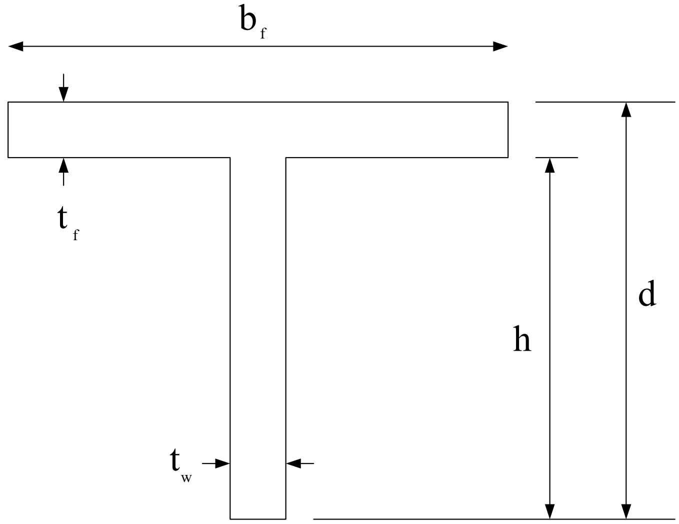


Figure 19 WTEE Beam Dimensions

In addition to the foregoing parametric variations, the thickness of the web, t_w, was also systematically varied throughout the study in order that the flexural ductility of the beam, observed via the rotation capacity, could be studied. With all of the basic beam cross-sectional dimensions defined as in Figure 19, the parametric studies are conducted through the use of ABAQUS.

An individual study was conducted for each of the eight b_f / d ratios identified. Taking, as an example, the trial where $b_f / d = 1.8$, the width of the flange is defined as $b_f = 1.8(d)$ where $d = 14"$. The thickness of the flange is determined based upon the ratio from equation (5-2). From the value of b_f as determined earlier, this ratio is subsequently used to calculate the thickness of the flange:

$$t_f = \frac{b_f}{65(2)} \tag{5-3}$$

Initially, the thickness of the web is given an assumed value. Using this value, the beam is analyzed and the normalized moment-rotation response is plotted in order to obtain the beam rotation capacity. Based upon the results of this analysis, the thickness of the web is either increased or decreased. This process is repeated until a thickness of the web is determined that will yield a moment rotation of approximately 3.0.

In order to draw conclusions in regards to the behavior of the beam when the thickness of the web approaches that necessary to produce an R-value of approximately 3.0, various parameters were recorded and tabulated. These results are shown in Section 5.2.

5.2 Presentation of Results

The results of the first three trials of the parametric studies are presented in Table 1. That is, the thickness of the web is varied while maintaining flange compactness, as per equation (5-1), for a given b/d ratio. Column 1 is an indication as to which trial is being analyzed. The span to depth ratio, L_{pd} / d, is also tabulated for later observations and conclusions. The ratio, $b_f / 2t_f$, is constant because, for these cases, equation (5-2) is satisfied. The values tabulated in the fourth column, h / t_w, the ratio of the height of the WTEE beam to the thickness of the web, is also tabulated for later observations and conclusions. M_u / M_p is the ratio of the maximum moment that the beam reached as compared with the calculated plastic moment of the beam. The last column is a tabulation of R, the rotation capacity, for each of the considered parametric combinations on the given row.

Table 1 Results of the First Three Trials

$\frac{b_f}{d}$	$\frac{L_{pd}}{d}$	$\frac{b_f}{2t_f}$	$\frac{h}{t_w}$	$\frac{M_u}{M_p}$	R
0.6	2.128	9.190	13.543	0.749	-
0.6	2.014	9.190	11.286	0.782	-
0.6	1.934	9.190	9.674	0.851	-
0.6	1.882	9.190	8.464	0.946	-
0.6	1.853	9.190	7.524	1.045	11.635
0.6	1.843	9.190	6.772	1.119	17.115
0.8	3.451	9.195	13.391	0.784	-
0.8	3.261	9.195	11.159	0.792	-
0.8	3.109	9.195	9.565	0.801	-
0.8	2.988	9.195	8.369	0.841	-
0.8	2.892	9.195	7.439	0.900	-
0.8	2.817	9.195	6.696	0.996	-
1.0	5.226	9.198	16.549	0.895	-
1.0	4.936	9.198	13.239	0.903	-
1.0	4.810	9.198	12.035	0.901	-
1.0	4.694	9.198	11.033	0.889	-
1.0	4.588	9.198	10.184	0.875	-

Table 2 summarizes the results from the remaining trials. The same ratios are tabulated for these cases.

Table 2 Parametric Studies with Acceptable Span to Depth Ratio

$\frac{b_f}{d}$	$\frac{L_{pd}}{d}$	$\frac{b_f}{2t_f}$	$\frac{h}{t_w}$	$\frac{M_u}{M_p}$	R
1.2	6.657	9.190	14.540	0.978	-
1.2	6.580	9.190	13.775	1.010	1.327
1.2	6.535	9.190	13.353	1.026	1.857
1.2	6.505	9.190	13.086	1.031	3.504
1.2	6.232	9.190	10.905	1.161	5.261
1.4	8.112	9.193	12.934	1.012	1.644
1.4	7.964	9.193	11.758	1.060	3.072
1.4	7.893	9.193	11.247	1.118	4.553
1.4	7.691	9.193	9.949	1.173	8.017
1.6	9.481	9.195	10.925	1.047	3.152
1.6	8.796	9.195	10.652	1.061	3.628
1.6	9.303	9.195	9.832	1.113	5.693
1.6	9.048	9.195	8.521	1.254	11.232
1.8	11.061	9.190	10.524	1.025	2.885
1.8	11.033	9.190	10.352	1.034	3.190
1.8	10.424	9.190	9.715	1.070	4.344
1.8	10.793	9.190	9.021	1.132	6.577
1.8	10.667	9.190	8.419	1.197	9.259
1.8	10.545	9.190	7.893	1.242	12.093
2.0	12.612	9.192	9.982	1.008	3.119
2.0	12.546	9.192	9.598	1.032	3.893
2.0	12.416	9.192	8.912	1.089	5.766
2.0	12.291	9.192	8.318	1.082	6.299

5.3 Increasing the Thickness of the Flange

The parametric studies were extended to include a study to explore the behavior of the same WTEE beam when the thickness of the flange was increased. The influence of the flange thickness was thought to be an important parameter for consideration since the flange-web junction of the WTEE may be thought of as being restrained by a linear spring whose stiffness is proportional to flange thickness. As a result, variation of the flange thickness ought to be considered in the study of cross-sectional parameters influencing WTEE flexural ductility.

For each of the eight variations of the ratio b_f / d considered, a final beam size was found that yielded a rotation capacity of approximately 3.0. It was these beams that were explored further within the context of this extension of the parametric study. This increase in the thickness of the flange was accomplished by altering the original slenderness ratio:

$$\frac{b_f}{2t_f} = \frac{65}{\sqrt{F_y}} \tag{5-4}$$

It is noted that the flange compactness given in equation (5-4) is for a flange in uniform compression; a condition that our WTEE flanges does not experience. The flange compactness criteria was used simply as a reasonable starting point from which to explore more slender tension flange alternatives. The first variation considered defined the flange slenderness ratio to be 20% greater than that necessary to produce a compact beam.

$$\frac{b_f}{2t_f} = 1.2\frac{65}{\sqrt{F_y}} \tag{5-5}$$

The thickness of the flange was varied for this analysis while all other dimensions were held constant. The purpose of this alteration was to observe the resulting behavior, and determine if increasing the thickness of the flange by 20% would affect the flexural ductility of the beam.

For each of the trials as described in Table 2, in which a rotation capacity of approximately 3.0 was obtained, the model was altered as described above. Because none of the models of Table 1 had a rotation capacity of approximately 3.0, none of these cases were further explored. An explanation of these cases is presented in Section 5.4. The results for the cases from Table 2 are presented below in Table 3.

Table 3 Increase of t_f by 20%

$\frac{b_f}{d}$	$\frac{L_{pd}}{d}$	$\frac{b_f}{2t_f}$	$\frac{h}{t_w}$	$\frac{M_u}{M_p}$	R
1.2	6.209	11.031	13.239	1.045	1.814
1.4	7.638	11.031	11.920	1.066	5.620
1.6	9.135	11.031	11.098	1.069	3.695
1.8	10.675	11.031	10.539	1.046	3.176
2.0	12.251	11.031	10.185	1.027	3.071

It is clear that for the cases where b_f / d =1.4 through 2.0, little change in the rotation capacity is observed. Noting that the value of the rotation capacity decreased for the case of b_f / d =1.2, further observations will be made to address this behavior in Section 5.4. More importantly, the flexural ductility of the beam is not decreased. Therefore, from these results, it can be observed that it is only necessary to fulfill the original slenderness ratio of equation (5-4).

A further increase in the thickness of the flange is explored to validate these observations. The ratio was then changed in order to increase equation (5-4) by 40%:

$$\frac{b_f}{2t} = 1.4\frac{65}{\sqrt{F_y}} \tag{5-6}$$

Again, the flexural ductility of the beam was observed through the calculation of the rotation capacity to determine if an increase in the thickness of the flange by 40% of the original thickness would affect the flexural ductility of the beam. The cases from Table 2 are presented below in Table 4.

Table 4 Increase of t_f by 40%

$\frac{b_f}{d}$	$\frac{L_{pd}}{d}$	$\frac{b_f}{2t_f}$	$\frac{h}{t_w}$	$\frac{M_u}{M_p}$	R
1.2	5.950	12.869	13.347	0.913	-
1.4	9.349	12.869	12.035	1.047	2.916
1.6	8.825	12.869	11.222	1.076	3.867
1.8	10.350	12.869	10.673	1.052	3.394
2.0	11.918	12.869	10.330	1.042	3.259

It is clear that for the cases of b_f / d equal to 1.4 through 2.0, this change has little effect on the rotation capacity. It is only necessary to note that there is no decrease in rotation capacity in these cases. However, for the instance of b_f / d equal to 1.2, a decrease in the rotation capacity is observed.

These results support the theory that the flange thickness need only satisfy equation (5-4). This, along with a sufficient web thickness will produce a compact beam.

5.4 Span to Depth Ratio

It was noted that the variations presented in Table 1 were not able to achieve a rotation capacity of approximately 3.0. In addition, when the thickness of the flange was increased, the case of $b_f / d = 1.2$, showed a decrease in the rotation capacity of the beam.

It was then observed from the ratios tabulated in these corresponding tables that the span to depth ratio was quite small; below 6.5. In these particular cases, the stress in the beam reached and exceeded the yield stress of the material as evidenced by viewing the von-Mises stresses of the beam. Figure 19 illustrates the von Mises stress distribution in a representative WTEE beam with low span-to-depth ratio. In these cases, the member is no longer conforming to Bernoulli-Euler beam behavior; the span to depth ratio is too small. As a result, the cross sectional material reaches yield prior to the attainment of sufficient longitudinal stress intensities, needed for attainment of M_p, as a result of the presence of large shear forces. From the parametric studies conducted throughout this section, it appears that a practical span-to-depth ratio needed for the attainment of M_p might be 6.5.

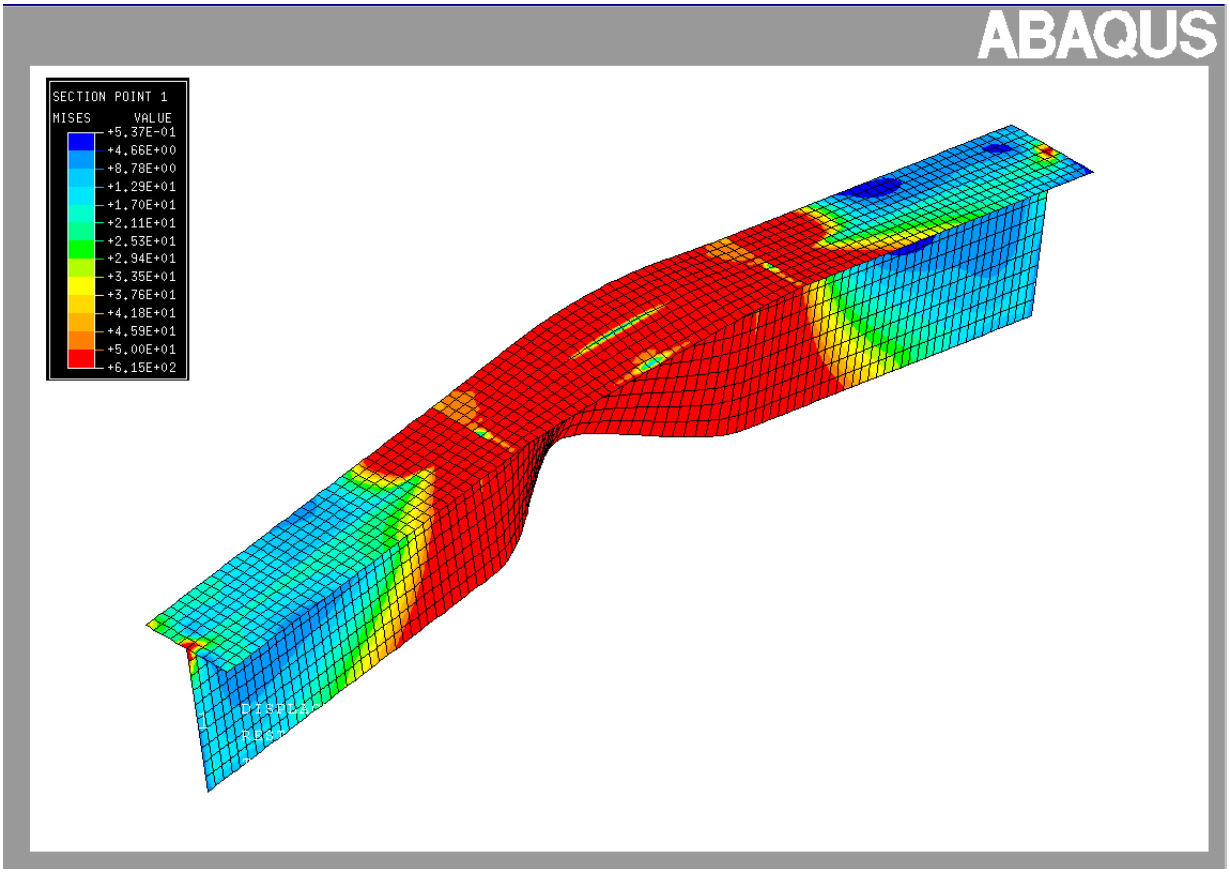


Figure 20 Failure Mode of WTEE Beam with a Low Value of L_{pd} / d

6.0 CONCLUSIONS

From the current research, it has been determined that correlations exist between the WTEE beam dimensions and the flexural ductility of the beam. This section will provide a summary of the requirements that must be satisfied in order to obtain a compact beam. These requirements are presented in the form of plate slenderness ratios.

The ratio of the height to the thickness of the web, h / t_w, followed a pattern throughout the current research. From the tables presented in Section 5, it is apparent that this ratio must be approximately equal to 10. $\frac{h}{t_w} \cong 10$

Additionally, for a WTEE beam subjected to negative flexure (stem in compression), the rotation capacity does not appear to be sensitive to the flange slenderness ratio, $b_f / 2t_f$, within a range that is consistent with hot-rolled steel member proportions.

Before the two previously enumerated plate slenderness requirements may be implemented, it is required that the beam satisfy a limitation on the span to depth ratio, L_{pd} / d. It has been determined through the parametric studies described in Section 5, and the explanation of Section 5.4, that this ratio must be greater than 6.5. If this requirement is not satisfied, high transverse shear forces may interfere with development of the full plastic capacity of the cross-section. $\frac{L_{pd}}{d} > 6.5$

Further research in this area would be beneficial in the development of additional applicable equations and limiting ratios.

APPENDIX A

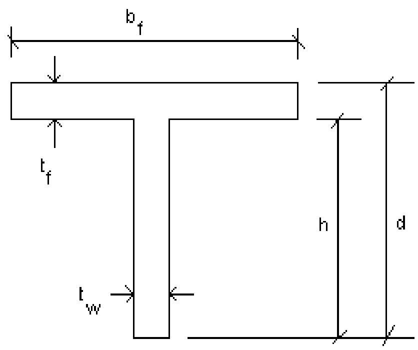
Input for ABAQUS

Prior to the WTEE being modeled in ABAQUS, certain properties and dimensions must be determined in order to create an accurate model. The first section of this appendix, A1, is a worksheet used to calculate the section properties of any particular WTEE shape. The original format for this file was MathCAD. The properties and dimensions calculated in this worksheet were inputted into an excel spreadsheet. This spreadsheet, presented in section A2 of this appendix, was designed to create an input file for ABAQUS. The spreadsheet was written in such a way that minimal alterations were necessary for each change of beam dimensions. The formulas involved in this spreadsheet are presented first, followed by an actual spreadsheet. Upon the completion of this step, an input file is easily created. A typical seed imperfection file and a material property file for one beam are presented to illustrate how each of the beams were inputted into ABAQUS. For Appendix A, the WTEE beam used as an illustrative example was that of $b_f / d = 2.0$ and $t_w = 1.25$, using the ratio, $b_f / 2t_f = 65 / \sqrt{F_y}$.

Appendix A1: Section Properties

Cross sectional properties for WTEE:

bf/d=2 var2_1.25



Assigned Properties:

$d := 14$ $E := 29000$ $G := 11200$ $Fy := 50$

$bf := 2 \cdot d$ $bf = 28$

$tf := \frac{bf \cdot \sqrt{Fy}}{65 \cdot 2}$ $tw := 1.25$ $h := d - tf$ $h = 12.477$

$tf = 1.523$ $\frac{h}{tw} = 9.982$

Calculations of Properties:

$A1 := bf \cdot tf$ $A2 := h \cdot tw$

$A1 = 42.644$ $A2 = 15.596$

Centroids measured from the bottom of the stem:

$y1 := \left(d - \frac{tf}{2}\right)$ $y2 := \frac{h}{2}$

$y1 = 13.239$ $y2 = 6.239$

Location of the Neutral Axis:

$$ybar := \frac{A1 \cdot y1 + A2 \cdot y2}{A1 + A2}$$

$ybar = 11.364$

Moment of Inertia about the X axis:

$$Ix := \frac{tw\cdot(h)^3}{12} + \left[A2\cdot(ybar - y2)^2\right] + \frac{bf\cdot tf^3}{12} + A1\cdot(y1 - ybar)^2$$

$$Ix = 770.138$$

$$Iy := \frac{(d - tf)\cdot tw^3}{12} + \frac{tf\cdot(bf)^3}{12}$$

$$Iy = 2.788 \times 10^3$$

Radius of Gyration:

$$rx := \sqrt{\frac{Ix}{A1 + A2}} \qquad ry := \sqrt{\frac{Iy}{A1 + A2}}$$

$$rx = 3.636 \qquad ry = 6.919$$

Section Modulus:

$$Cfl := d - ybar \qquad Cst := ybar \qquad Cw := 0$$

$$Sfl := \frac{Ix}{Cfl} \qquad Sst := \frac{Ix}{Cst}$$

Polar Moment of Inertia:

$$J := \frac{bf\cdot(tf)^3}{3} + \frac{(d - tf)\cdot(tw)^3}{3}$$

First Calculation of Plastic Section Modulus

Location of the Plastic Neutral Axis

$$Y1_a := \frac{bf \cdot tf - h \cdot tw}{bf} \qquad Y2_a := \frac{h \cdot tw - bf \cdot tf}{tw}$$

Plastic Section Modulus

$$Za := \frac{\left(tf - Y1_a\right)^2}{2} \cdot bf + \left(\frac{{Y1_a}^2}{2} \cdot bf\right) + \frac{h^2}{2} \cdot tw$$

$$Zb := bf \cdot tf \cdot \left(\frac{tf}{2} + Y2_a\right) + \left(\frac{tw^2}{2} \cdot Y2_a\right) + \frac{(h - tw)^2}{2} \cdot tw$$

$$Z1 := \text{if}(A2 < A1, Za, Zb)$$

$$Z1 = 114.705$$

Second Calculation of Plastic Section Modulus

Location of the Plastic Neutral Axis:

$$Y1 := \frac{bf \cdot tf + tf \cdot tw - d \cdot tw}{2 \cdot bf} \qquad Y2 := \frac{d \cdot tw - tf \cdot tw - bf \cdot tf}{2 \cdot tw}$$

$$Y1 = 0.483 \qquad Y2 = -10.819$$

Plastic Section Modulus:

$$Z_1 := \left[\left(\frac{tf - Y1}{2} + Y1\right) \cdot (tf - Y1) \cdot bf\right] + \left[\frac{Y1^2}{2} \cdot bf + \left[\left(\frac{d - tf}{2}\right) + Y1\right] \cdot (d - tf) \cdot tw\right]$$

$$Z_2 := bf \cdot tf \cdot \left(\frac{tf}{2} + Y2\right) + \left[\frac{(d - tf - Y2)^2}{2} \cdot tw + \frac{Y2^2 \cdot tw}{2}\right]$$

$$Z2 := \text{if}\left(A2 < A1, Z_1, Z_2\right)$$

$$Z2 = 137.304$$

Final Plastic Section Modulus

$$Z := \frac{Z1 + Z2}{2}$$

$$Z = 126.004$$

Plastic Moment:

Calculated

$$Mp := Z \cdot Fy$$

$$Mp = 6.3 \times 10^3$$

Summary :

Areas:

$A1 = 42.644 \qquad A2 = 15.596 \qquad A1 + A2 = 58.24$

Slenderness Ratios:

$$\frac{bf}{2 \cdot tf} = 9.192 \qquad \frac{h}{tw} = 9.982 \qquad \frac{tw}{2} = 0.625$$

Moments of Inertia and Radius of Gyration:

$Ix = 770.138 \qquad rx = 3.636 \qquad Iy = 2.788 \times 10^3 \quad ry = 6.919$

Elastic Section Moduli:

$Sst = 67.77 \qquad Sfl = 292.157 \qquad J = 41.094$

Plastic Section Modulus:

$Z = 126.004$

Unbraced Length:

$$Lb := [\,0.12 + 0.076 \cdot (-1)\,] \cdot \left(\frac{E}{Fy}\right) \cdot ry \qquad Lb = 176.573$$

Plastic Moment:

$Mp := Z \cdot Fy \qquad Mp = 6.3 \times 10^3$

Yield Moment:

$My := Fy \cdot Sst \qquad My = 3.389 \times 10^3$

Maximum Deflection:

$$\Delta_{max} := \frac{Mp}{24 \cdot E \cdot Ix} \cdot \left[3 \cdot (3 \cdot Lb)^2 - 4 \cdot (Lb)^2\right] \qquad \Delta_{max} = 8.429$$

Rotation:

$$\theta p := \frac{Mp \cdot Lb}{2 \cdot E \cdot Ix} \qquad \theta p = 0.0249$$

Span to Depth Ratio:

$$\frac{Lb}{d} = 12.612$$

Filename		var2_1.25					
*Heading							
alter tw while bf/d=2.0							
RIGID ENDS							
S9R5 ELEMENTS							
APPROXIMATELY 1" ELEMENTS							
ACTUAL WTEE DIMENSIONS							
**							
**INITIAL CONDITIONS							
**							
	INPUT VARIBLES						
				STEEL			
		INCHES			KSI		
		Lb= 176.573			E= 29000		
		L= =3*C19			Fy= 50		
		bf= 28			v= 0.3		
		d= 14					
		tf= 1.523			RIGID		
		tw= 1.25			E= 290000		
	NUMBER OF ELEMENTS IN FLANGE			10	THIS NUMBER CAN E		
	NUMBER OF ELEMENTS IN LENGTH			=C19/E29			
	FLANGE ELEMENT SIZE			=C21/E26		midpoint	=((A49+A51)/2)+((E40+1)/2)
	LENGTH ELEMENT SIZE			=(C19)/(ROUND(E27,0))			
	WEB ELEMENT SIZE			1.4125			
	MESH SETUP						
		EL FL	=C21/E29	=ROUND(D35,0)		THIS SHOULD BE EVEN	
		EL Lb	=C19/E30	=ROUND(D36,0)			
		EL WB	=C22/E31-1	=ROUND(D37,0)			
		STITCH	=C22-(E31*E37)	=ROUND(D38,3)			
		FLANGE LENGTH INC		=E35*2+1			
		FLANGE INC		=E40-1			
		WEB LENGTH INC		=E37*2+1			
		WEB INC		=E42-1			
	INITIAL COORIDINATES						
*NODE							
1	0	0	0				
=E35*2+1	0	=E29*E35	0				
=2*E36*E40+A47	=E30*E36	0	0				
=A49+E41	=E30*E36	=E29*E35	0				
=2*E36*E40+A49	=2*E30*E36	0	0				
=A51+E41	=2*E30*E36	=E29*E35	0				
=2*E36*E40+A51	=3*E30*E36	0	0				
=A53+E41	=3*E30*E36	=E29*E35	0				
=A54+1	0	=(E29*E35)/2	=-((E31*E37)+E38)				
=A55+E43	0	=(E29*E35)/2	=-E38				
=2*E36*E42+A55	=E30*E36	=(E29*E35)/2	=-((E31*E37)+E38)				
=A57+E43	=E30*E36	=(E29*E35)/2	=-E38				
=2*E36*E42+A57	=2*(E30*E36)	=(E29*E35)/2	=-((E31*E37)+E38)				
=A59+E43	=2*(E30*E36)	=(E29*E35)/2	=-E38				
=2*E36*E42+A59	=3*(E30*E36)	=(E29*E35)/2	=-((E31*E37)+E38)				
=A61+E43	=3*(E30*E36)	=(E29*E35)/2	=-E38				
51000	=0	=(E29*E35)/2	=-(E38/2)		First node of stitch, sta		
=(2*3*E36+A63)	=3*(E30*E36)	=(E29*E35)/2	=-(E38/2)		must be greater than la		

```
**
**NODE DEFINITION
**
*NGEN        NSET=BFLANGELT
=A47         =A49            =E40
*NGEN        NSET=TFLANGELT
=A48         =A50            =E40
*NGEN        NSET=BFLANGEMID
=A49         =A51            =E40
*NGEN        NSET=TFLANGEMID
=A50         =A52            =E40
*NGEN        NSET=BFLANGERT
=A51         =A53            =E40
*NGEN        NSET=TFLANGERT
=A52         =A54            =E40
*NGEN        NSET=BWEBLT
=A55         =A57            =E42
*NGEN        NSET=TWEBLT
=A56         =A58            =E42
*NGEN        NSET=BWEBMID
=A57         =A59            =E42
*NGEN        NSET=TWEBMID
=A58         =A60            =E42
*NGEN        NSET=BWEBRT
=A59         =A61            =E42
*NGEN        NSET=TWEBRT
=A60         =A62            =E42
*NGEN        NSET=STITCH
=A63         =A64            =1

**
**FILL NODES
**

*NFILL       NSET=FLANGELT
BFLANGELT    TFLANGELT       =E41
*NFILL       NSET=FLANGEMID
BFLANGEMID   TFLANGEMID      =E41
*NFILL       NSET=FLANGERT
BFLANGERT    TFLANGERT       =E41
*NFILL       NSET=WEBLT
BWEBLT       TWEBLT          =E43
*NFILL       NSET=WEBMID
BWEBMID      TWEBMID         =E43
*NFILL       NSET=WEBRT
BWEBRT       TWEBRT          =E43

**
**CONSTRAINT SETS
**

*NSET        NSET=FLPINLT    GENERATE
=A47         =A48            1
*NSET        NSET=FLPINRT    GENERATE
=A53         =A54            1
*NSET        NSET=WEBPINLT   GENERATE
=A55         =A56            1
*NSET        NSET=WEBPINRT   GENERATE
=A61         =A62            1
*NSET        NSET=MIDPINLT   GENERATE
=A57         =A58            1
*NSET        NSET=MIDPINRT   GENERATE
=A59         =A60            1
*NSET        NSET=LTLOAD     GENERATE
=A49         =A50            1
*NSET        NSET=RTLOAD     GENERATE
=A51         =A52            1
```

**									
**FLANGELT									
**									
	MASTER ELEMENT								
*ELEMENT	TYPE=S9R5								
1	=A47	=(A47+E40)+E40	=C139+2	=B139+2	=B139+E40	=C139+1	=F139+2	=B139+1	=F139+1
	GENERATE ELEMENT SET								
*ELGEN	ELSET=FLANGELT								
=A139	=$E$36	=$A$47+$E$40+$E$4(	1	=$E$35	=2	=(3*$E$36)			
**									
**FLANGEMID									
**									
*ELEMENT	TYPE=S9R5								
=E36+1	=A49	=(A49+E40+E40)	=C147+2	=B147+2	=B147+E40	=C147+1	=E147+E40	=B147+1	=F147+1
*ELGEN	ELSET=FLANGEMID								
=A147	=$E$36	=$A$47+$E$40+$E$4(	1	=$E$35	=2	=(3*$E$36)			
**									
**FLANGERT									
**									
*ELEMENT	TYPE=S9R5								
=2*E36+1	=A51	=A51+E40+E40	=C154+2	=B154+2	=B154+E40	=C154+1	=E154+E40	=B154+1	=F154+1
*ELGEN	ELSET=FLANGERT								
=A154	=$E$36	=$A$47+$E$40+$E$4(	1	=$E$35	=2	=(3*$E$36)			
**									
**WEBLT									
**									
*ELEMENT	TYPE=S9R5								
=(3*E36)*E35+1	=A55	=A55+E42+E42	=C161+2	=B161+2	=B161+E42	=C161+1	=E161+E42	=B161+1	=F161+1
*ELGEN	ELSET=WEBLT								
=A161	=$E$36	=$E$42+$E$42	1	=$E$37	=2	=(3*$E$36)			
**									
**WEBMID									
**									
*ELEMENT	TYPE=S9R5								
=E36+A163	=A57	=A57+E42+E42	=C168+2	=B168+2	=A57+E42	=C168+1	=E168+E42	=B168+1	=F168+1
*ELGEN	ELSET=WEBMID								
=A168	=$E$36	=C163	1	=$E$37	=2	=(3*$E$36)			
**									
**WEBRT									
**									
*ELEMENT	TYPE=S9R5								
=A170+E36	=A59	=A59+E42+E42	=C175+2	=B175+2	=B175+E42	=C175+1	=E175+E42	=B175+1	=F175+1
*ELGEN	ELSET=WEBRT								
=A175	=$E$36	=C163	1	=$E$37	=2	=(3*$E$36)			

**
**STITCHLT
**

*ELEMENT	TYPE=S9R5									
=3*E36*E37+A161	=A56	=B182+E42+E42	=E182+E40+E40	=(A48+1)/2	=B182+E42	=A63+2	=E182+E40	=A63	=I182+1	=IF(C182=$A$58,"STOP","")
=A182+1	=C182	=B183+$E$42+$E$42	=D182+$E$40+$E$40	=D182	=C182+$E$42	=G182+2	=E183+$E$40	=G182	=I183+1	=IF(C183=$A$58,"STOP","")
=A183+1	=C183	=B184+$E$42+$E$42	=D183+$E$40+$E$40	=D183	=C183+$E$42	=G183+2	=E184+$E$40	=G183	=I184+1	=IF(C184=$A$58,"STOP","")
=A184+1	=C184	=B185+$E$42+$E$42	=D184+$E$40+$E$40	=D184	=C184+$E$42	=G184+2	=E185+$E$40	=G184	=I185+1	=IF(C185=$A$58,"STOP","")
=A185+1	=C185	=B186+$E$42+$E$42	=D185+$E$40+$E$40	=D185	=C185+$E$42	=G185+2	=E186+$E$40	=G185	=I186+1	=IF(C186=$A$58,"STOP","")
=A186+1	=C186	=B187+$E$42+$E$42	=D186+$E$40+$E$40	=D186	=C186+$E$42	=G186+2	=E187+$E$40	=G186	=I187+1	=IF(C187=$A$58,"STOP","")
=A187+1	=C187	=B188+$E$42+$E$42	=D187+$E$40+$E$40	=D187	=C187+$E$42	=G187+2	=E188+$E$40	=G187	=I188+1	=IF(C188=$A$58,"STOP","")
=A188+1	=C188	=B189+$E$42+$E$42	=D188+$E$40+$E$40	=D188	=C188+$E$42	=G188+2	=E189+$E$40	=G188	=I189+1	=IF(C189=$A$58,"STOP","")
=A189+1	=C189	=B190+$E$42+$E$42	=D189+$E$40+$E$40	=D189	=C189+$E$42	=G189+2	=E190+$E$40	=G189	=I190+1	=IF(C190=$A$58,"STOP","")
=A190+1	=C190	=B191+$E$42+$E$42	=D190+$E$40+$E$40	=D190	=C190+$E$42	=G190+2	=E191+$E$40	=G190	=I191+1	=IF(C191=$A$58,"STOP","")
=A191+1	=C191	=B192+$E$42+$E$42	=D191+$E$40+$E$40	=D191	=C191+$E$42	=G191+2	=E192+$E$40	=G191	=I192+1	=IF(C192=$A$58,"STOP","")
=A192+1	=C192	=B193+$E$42+$E$42	=D192+$E$40+$E$40	=D192	=C192+$E$42	=G192+2	=E193+$E$40	=G192	=I193+1	=IF(C193=$A$58,"STOP","")
=A193+1	=C193	=B194+$E$42+$E$42	=D193+$E$40+$E$40	=D193	=C193+$E$42	=G193+2	=E194+$E$40	=G193	=I194+1	=IF(C194=$A$58,"STOP","")
=A194+1	=C194	=B195+$E$42+$E$42	=D194+$E$40+$E$40	=D194	=C194+$E$42	=G194+2	=E195+$E$40	=G194	=I195+1	=IF(C195=$A$58,"STOP","")
=A195+1	=C195	=B196+$E$42+$E$42	=D195+$E$40+$E$40	=D195	=C195+$E$42	=G195+2	=E196+$E$40	=G195	=I196+1	=IF(C196=$A$58,"STOP","")
=A196+1	=C196	=B197+$E$42+$E$42	=D196+$E$40+$E$40	=D196	=C196+$E$42	=G196+2	=E197+$E$40	=G196	=I197+1	=IF(C197=$A$58,"STOP","")
=A197+1	=C197	=B198+$E$42+$E$42	=D197+$E$40+$E$40	=D197	=C197+$E$42	=G197+2	=E198+$E$40	=G197	=I198+1	=IF(C198=$A$58,"STOP","")
=A198+1	=C198	=B199+$E$42+$E$42	=D198+$E$40+$E$40	=D198	=C198+$E$42	=G198+2	=E199+$E$40	=G198	=I199+1	=IF(C199=$A$58,"STOP","")
=A199+1	=C199	=B200+$E$42+$E$42	=D199+$E$40+$E$40	=D199	=C199+$E$42	=G199+2	=E200+$E$40	=G199	=I200+1	=IF(C200=$A$58,"STOP","")
=A200+1	=C200	=B201+$E$42+$E$42	=D200+$E$40+$E$40	=D200	=C200+$E$42	=G200+2	=E201+$E$40	=G200	=I201+1	=IF(C201=$A$58,"STOP","")
=A201+1	=C201	=B202+$E$42+$E$42	=D201+$E$40+$E$40	=D201	=C201+$E$42	=G201+2	=E202+$E$40	=G201	=I202+1	=IF(C202=$A$58,"STOP","")
=A202+1	=C202	=B203+$E$42+$E$42	=D202+$E$40+$E$40	=D202	=C202+$E$42	=G202+2	=E203+$E$40	=G202	=I203+1	=IF(C203=$A$58,"STOP","")
=A203+1	=C203	=B204+$E$42+$E$42	=D203+$E$40+$E$40	=D203	=C203+$E$42	=G203+2	=E204+$E$40	=G203	=I204+1	=IF(C204=$A$58,"STOP","")
=A204+1	=C204	=B205+$E$42+$E$42	=D204+$E$40+$E$40	=D204	=C204+$E$42	=G204+2	=E205+$E$40	=G204	=I205+1	=IF(C205=$A$58,"STOP","")
=A205+1	=C205	=B206+$E$42+$E$42	=D205+$E$40+$E$40	=D205	=C205+$E$42	=G205+2	=E206+$E$40	=G205	=I206+1	=IF(C206=$A$58,"STOP","")
=A206+1	=C206	=B207+$E$42+$E$42	=D206+$E$40+$E$40	=D206	=C206+$E$42	=G206+2	=E207+$E$40	=G206	=I207+1	=IF(C207=$A$58,"STOP","")
=A207+1	=C207	=B208+$E$42+$E$42	=D207+$E$40+$E$40	=D207	=C207+$E$42	=G207+2	=E208+$E$40	=G207	=I208+1	=IF(C208=$A$58,"STOP","")
=A208+1	=C208	=B209+$E$42+$E$42	=D208+$E$40+$E$40	=D208	=C208+$E$42	=G208+2	=E209+$E$40	=G208	=I209+1	=IF(C209=$A$58,"STOP","")
=A209+1	=C209	=B210+$E$42+$E$42	=D209+$E$40+$E$40	=D209	=C209+$E$42	=G209+2	=E210+$E$40	=G209	=I210+1	=IF(C210=$A$58,"STOP","")
=A210+1	=C210	=B211+$E$42+$E$42	=D210+$E$40+$E$40	=D210	=C210+$E$42	=G210+2	=E211+$E$40	=G210	=I211+1	=IF(C211=$A$58,"STOP","")
=A211+1	=C211	=B212+$E$42+$E$42	=D211+$E$40+$E$40	=D211	=C211+$E$42	=G211+2	=E212+$E$40	=G211	=I212+1	=IF(C212=$A$58,"STOP","")
=A212+1	=C212	=B213+$E$42+$E$42	=D212+$E$40+$E$40	=D212	=C212+$E$42	=G212+2	=E213+$E$40	=G212	=I213+1	=IF(C213=$A$58,"STOP","")
=A213+1	=C213	=B214+$E$42+$E$42	=D213+$E$40+$E$40	=D213	=C213+$E$42	=G213+2	=E214+$E$40	=G213	=I214+1	=IF(C214=$A$58,"STOP","")
=A214+1	=C214	=B215+$E$42+$E$42	=D214+$E$40+$E$40	=D214	=C214+$E$42	=G214+2	=E215+$E$40	=G214	=I215+1	=IF(C215=$A$58,"STOP","")
=A215+1	=C215	=B216+$E$42+$E$42	=D215+$E$40+$E$40	=D215	=C215+$E$42	=G215+2	=E216+$E$40	=G215	=I216+1	=IF(C216=$A$58,"STOP","")
=A216+1	=C216	=B217+$E$42+$E$42	=D216+$E$40+$E$40	=D216	=C216+$E$42	=G216+2	=E217+$E$40	=G216	=I217+1	=IF(C217=$A$58,"STOP","")
=A217+1	=C217	=B218+$E$42+$E$42	=D217+$E$40+$E$40	=D217	=C217+$E$42	=G217+2	=E218+$E$40	=G217	=I218+1	=IF(C218=$A$58,"STOP","")
=A218+1	=C218	=B219+$E$42+$E$42	=D218+$E$40+$E$40	=D218	=C218+$E$42	=G218+2	=E219+$E$40	=G218	=I219+1	=IF(C219=$A$58,"STOP","")
=A219+1	=C219	=B220+$E$42+$E$42	=D219+$E$40+$E$40	=D219	=C219+$E$42	=G219+2	=E220+$E$40	=G219	=I220+1	=IF(C220=$A$58,"STOP","")
=A220+1	=C220	=B221+$E$42+$E$42	=D220+$E$40+$E$40	=D220	=C220+$E$42	=G220+2	=E221+$E$40	=G220	=I221+1	=IF(C221=$A$58,"STOP","")
=A221+1	=C221	=B222+$E$42+$E$42	=D221+$E$40+$E$40	=D221	=C221+$E$42	=G221+2	=E222+$E$40	=G221	=I222+1	=IF(C222=$A$58,"STOP","")
=A222+1	=C222	=B223+$E$42+$E$42	=D222+$E$40+$E$40	=D222	=C222+$E$42	=G222+2	=E223+$E$40	=G222	=I223+1	=IF(C223=$A$58,"STOP","")
=A223+1	=C223	=B224+$E$42+$E$42	=D223+$E$40+$E$40	=D223	=C223+$E$42	=G223+2	=E224+$E$40	=G223	=I224+1	=IF(C224=$A$58,"STOP","")
=A224+1	=C224	=B225+$E$42+$E$42	=D224+$E$40+$E$40	=D224	=C224+$E$42	=G224+2	=E225+$E$40	=G224	=I225+1	=IF(C225=$A$58,"STOP","")
=A225+1	=C225	=B226+$E$42+$E$42	=D225+$E$40+$E$40	=D225	=C225+$E$42	=G225+2	=E226+$E$40	=G225	=I226+1	=IF(C226=$A$58,"STOP","")
=A226+1	=C226	=B227+$E$42+$E$42	=D226+$E$40+$E$40	=D226	=C226+$E$42	=G226+2	=E227+$E$40	=G226	=I227+1	=IF(C227=$A$58,"STOP","")
=A227+1	=C227	=B228+$E$42+$E$42	=D227+$E$40+$E$40	=D227	=C227+$E$42	=G227+2	=E228+$E$40	=G227	=I228+1	=IF(C228=$A$58,"STOP","")
=A228+1	=C228	=B229+$E$42+$E$42	=D228+$E$40+$E$40	=D228	=C228+$E$42	=G228+2	=E229+$E$40	=G228	=I229+1	=IF(C229=$A$58,"STOP","")
=A229+1	=C229	=B230+$E$42+$E$42	=D229+$E$40+$E$40	=D229	=C229+$E$42	=G229+2	=E230+$E$40	=G229	=I230+1	=IF(C230=$A$58,"STOP","")
=A230+1	=C230	=B231+$E$42+$E$42	=D230+$E$40+$E$40	=D230	=C230+$E$42	=G230+2	=E231+$E$40	=G230	=I231+1	=IF(C231=$A$58,"STOP","")
=A231+1	=C231	=B232+$E$42+$E$42	=D231+$E$40+$E$40	=D231	=C231+$E$42	=G231+2	=E232+$E$40	=G231	=I232+1	=IF(C232=$A$58,"STOP","")
=A232+1	=C232	=B233+$E$42+$E$42	=D232+$E$40+$E$40	=D232	=C232+$E$42	=G232+2	=E233+$E$40	=G232	=I233+1	=IF(C233=$A$58,"STOP","")
=A233+1	=C233	=B234+$E$42+$E$42	=D233+$E$40+$E$40	=D233	=C233+$E$42	=G233+2	=E234+$E$40	=G233	=I234+1	=IF(C234=$A$58,"STOP","")
=A234+1	=C234	=B235+$E$42+$E$42	=D234+$E$40+$E$40	=D234	=C234+$E$42	=G234+2	=E235+$E$40	=G234	=I235+1	=IF(C235=$A$58,"STOP","")
=A235+1	=C235	=B236+$E$42+$E$42	=D235+$E$40+$E$40	=D235	=C235+$E$42	=G235+2	=E236+$E$40	=G235	=I236+1	=IF(C236=$A$58,"STOP","")
=A236+1	=C236	=B237+$E$42+$E$42	=D236+$E$40+$E$40	=D236	=C236+$E$42	=G236+2	=E237+$E$40	=G236	=I237+1	=IF(C237=$A$58,"STOP","")
=A237+1	=C237	=B238+$E$42+$E$42	=D237+$E$40+$E$40	=D237	=C237+$E$42	=G237+2	=E238+$E$40	=G237	=I238+1	=IF(C238=$A$58,"STOP","")
=A238+1	=C238	=B239+$E$42+$E$42	=D238+$E$40+$E$40	=D238	=C238+$E$42	=G238+2	=E239+$E$40	=G238	=I239+1	=IF(C239=$A$58,"STOP","")
=A239+1	=C239	=B240+$E$42+$E$42	=D239+$E$40+$E$40	=D239	=C239+$E$42	=G239+2	=E240+$E$40	=G239	=I240+1	=IF(C240=$A$58,"STOP","")
=A240+1	=C240	=B241+$E$42+$E$42	=D240+$E$40+$E$40	=D240	=C240+$E$42	=G240+2	=E241+$E$40	=G240	=I241+1	=IF(C241=$A$58,"STOP","")
=A241+1	=C241	=B242+$E$42+$E$42	=D241+$E$40+$E$40	=D241	=C241+$E$42	=G241+2	=E242+$E$40	=G241	=I242+1	=IF(C242=$A$58,"STOP","")
=A242+1	=C242	=B243+$E$42+$E$42	=D242+$E$40+$E$40	=D242	=C242+$E$42	=G242+2	=E243+$E$40	=G242	=I243+1	=IF(C243=$A$58,"STOP","")
=A243+1	=C243	=B244+$E$42+$E$42	=D243+$E$40+$E$40	=D243	=C243+$E$42	=G243+2	=E244+$E$40	=G243	=I244+1	=IF(C244=$A$58,"STOP","")
*ELSET	ELSET=STITCHLT	GENERATE								
=A182	=A244	1								

**
**STITCHMID
**

*ELEMENT	TYPE=S9R5									
=A182+E36	=A58	=B251+E42+E42	=E251+E40+E40	=E182+2*E36*E40	=B251+E42	=J244+3	=E251+E40	=G251-2	=I251+1	=IF(C251=$A$60,"STOP","")
=A251+1	=C251	=B252+$E$42+$E$42	=D251+$E$40+$E$40	=D251	=B252+$E$42	=G251+2	=E252+$E$40	=G251	=I252+1	=IF(C252=$A$60,"STOP","")
=A252+1	=C252	=B253+$E$42+$E$42	=D252+$E$40+$E$40	=D252	=B253+$E$42	=G252+2	=E253+$E$40	=G252	=I253+1	=IF(C253=$A$60,"STOP","")
=A253+1	=C253	=B254+$E$42+$E$42	=D253+$E$40+$E$40	=D253	=B254+$E$42	=G253+2	=E254+$E$40	=G253	=I254+1	=IF(C254=$A$60,"STOP","")
=A254+1	=C254	=B255+$E$42+$E$42	=D254+$E$40+$E$40	=D254	=B255+$E$42	=G254+2	=E255+$E$40	=G254	=I255+1	=IF(C255=$A$60,"STOP","")
=A255+1	=C255	=B256+$E$42+$E$42	=D255+$E$40+$E$40	=D255	=B256+$E$42	=G255+2	=E256+$E$40	=G255	=I256+1	=IF(C256=$A$60,"STOP","")
=A256+1	=C256	=B257+$E$42+$E$42	=D256+$E$40+$E$40	=D256	=B257+$E$42	=G256+2	=E257+$E$40	=G256	=I257+1	=IF(C257=$A$60,"STOP","")
=A257+1	=C257	=B258+$E$42+$E$42	=D257+$E$40+$E$40	=D257	=B258+$E$42	=G257+2	=E258+$E$40	=G257	=I258+1	=IF(C258=$A$60,"STOP","")
=A258+1	=C258	=B259+$E$42+$E$42	=D258+$E$40+$E$40	=D258	=B259+$E$42	=G258+2	=E259+$E$40	=G258	=I259+1	=IF(C259=$A$60,"STOP","")
=A259+1	=C259	=B260+$E$42+$E$42	=D259+$E$40+$E$40	=D259	=B260+$E$42	=G259+2	=E260+$E$40	=G259	=I260+1	=IF(C260=$A$60,"STOP","")
=A260+1	=C260	=B261+$E$42+$E$42	=D260+$E$40+$E$40	=D260	=B261+$E$42	=G260+2	=E261+$E$40	=G260	=I261+1	=IF(C261=$A$60,"STOP","")
=A261+1	=C261	=B262+$E$42+$E$42	=D261+$E$40+$E$40	=D261	=B262+$E$42	=G261+2	=E262+$E$40	=G261	=I262+1	=IF(C262=$A$60,"STOP","")
=A262+1	=C262	=B263+$E$42+$E$42	=D262+$E$40+$E$40	=D262	=B263+$E$42	=G262+2	=E263+$E$40	=G262	=I263+1	=IF(C263=$A$60,"STOP","")
=A263+1	=C263	=B264+$E$42+$E$42	=D263+$E$40+$E$40	=D263	=B264+$E$42	=G263+2	=E264+$E$40	=G263	=I264+1	=IF(C264=$A$60,"STOP","")
=A264+1	=C264	=B265+$E$42+$E$42	=D264+$E$40+$E$40	=D264	=B265+$E$42	=G264+2	=E265+$E$40	=G264	=I265+1	=IF(C265=$A$60,"STOP","")
=A265+1	=C265	=B266+$E$42+$E$42	=D265+$E$40+$E$40	=D265	=B266+$E$42	=G265+2	=E266+$E$40	=G265	=I266+1	=IF(C266=$A$60,"STOP","")
=A266+1	=C266	=B267+$E$42+$E$42	=D266+$E$40+$E$40	=D266	=B267+$E$42	=G266+2	=E267+$E$40	=G266	=I267+1	=IF(C267=$A$60,"STOP","")
=A267+1	=C267	=B268+$E$42+$E$42	=D267+$E$40+$E$40	=D267	=B268+$E$42	=G267+2	=E268+$E$40	=G267	=I268+1	=IF(C268=$A$60,"STOP","")
=A268+1	=C268	=B269+$E$42+$E$42	=D268+$E$40+$E$40	=D268	=B269+$E$42	=G268+2	=E269+$E$40	=G268	=I269+1	=IF(C269=$A$60,"STOP","")
=A269+1	=C269	=B270+$E$42+$E$42	=D269+$E$40+$E$40	=D269	=B270+$E$42	=G269+2	=E270+$E$40	=G269	=I270+1	=IF(C270=$A$60,"STOP","")
=A270+1	=C270	=B271+$E$42+$E$42	=D270+$E$40+$E$40	=D270	=B271+$E$42	=G270+2	=E271+$E$40	=G270	=I271+1	=IF(C271=$A$60,"STOP","")
=A271+1	=C271	=B272+$E$42+$E$42	=D271+$E$40+$E$40	=D271	=B272+$E$42	=G271+2	=E272+$E$40	=G271	=I272+1	=IF(C272=$A$60,"STOP","")
=A272+1	=C272	=B273+$E$42+$E$42	=D272+$E$40+$E$40	=D272	=B273+$E$42	=G272+2	=E273+$E$40	=G272	=I273+1	=IF(C273=$A$60,"STOP","")
=A273+1	=C273	=B274+$E$42+$E$42	=D273+$E$40+$E$40	=D273	=B274+$E$42	=G273+2	=E274+$E$40	=G273	=I274+1	=IF(C274=$A$60,"STOP","")
=A274+1	=C274	=B275+$E$42+$E$42	=D274+$E$40+$E$40	=D274	=B275+$E$42	=G274+2	=E275+$E$40	=G274	=I275+1	=IF(C275=$A$60,"STOP","")
=A275+1	=C275	=B276+$E$42+$E$42	=D275+$E$40+$E$40	=D275	=B276+$E$42	=G275+2	=E276+$E$40	=G275	=I276+1	=IF(C276=$A$60,"STOP","")
=A276+1	=C276	=B277+$E$42+$E$42	=D276+$E$40+$E$40	=D276	=B277+$E$42	=G276+2	=E277+$E$40	=G276	=I277+1	=IF(C277=$A$60,"STOP","")
=A277+1	=C277	=B278+$E$42+$E$42	=D277+$E$40+$E$40	=D277	=B278+$E$42	=G277+2	=E278+$E$40	=G277	=I278+1	=IF(C278=$A$60,"STOP","")
=A278+1	=C278	=B279+$E$42+$E$42	=D278+$E$40+$E$40	=D278	=B279+$E$42	=G278+2	=E279+$E$40	=G278	=I279+1	=IF(C279=$A$60,"STOP","")
=A279+1	=C279	=B280+$E$42+$E$42	=D279+$E$40+$E$40	=D279	=B280+$E$42	=G279+2	=E280+$E$40	=G279	=I280+1	=IF(C280=$A$60,"STOP","")
=A280+1	=C280	=B281+$E$42+$E$42	=D280+$E$40+$E$40	=D280	=B281+$E$42	=G280+2	=E281+$E$40	=G280	=I281+1	=IF(C281=$A$60,"STOP","")
=A281+1	=C281	=B282+$E$42+$E$42	=D281+$E$40+$E$40	=D281	=B282+$E$42	=G281+2	=E282+$E$40	=G281	=I282+1	=IF(C282=$A$60,"STOP","")
=A282+1	=C282	=B283+$E$42+$E$42	=D282+$E$40+$E$40	=D282	=B283+$E$42	=G282+2	=E283+$E$40	=G282	=I283+1	=IF(C283=$A$60,"STOP","")
=A283+1	=C283	=B284+$E$42+$E$42	=D283+$E$40+$E$40	=D283	=B284+$E$42	=G283+2	=E284+$E$40	=G283	=I284+1	=IF(C284=$A$60,"STOP","")
=A284+1	=C284	=B285+$E$42+$E$42	=D284+$E$40+$E$40	=D284	=B285+$E$42	=G284+2	=E285+$E$40	=G284	=I285+1	=IF(C285=$A$60,"STOP","")
=A285+1	=C285	=B286+$E$42+$E$42	=D285+$E$40+$E$40	=D285	=B286+$E$42	=G285+2	=E286+$E$40	=G285	=I286+1	=IF(C286=$A$60,"STOP","")
=A286+1	=C286	=B287+$E$42+$E$42	=D286+$E$40+$E$40	=D286	=B287+$E$42	=G286+2	=E287+$E$40	=G286	=I287+1	=IF(C287=$A$60,"STOP","")
=A287+1	=C287	=B288+$E$42+$E$42	=D287+$E$40+$E$40	=D287	=B288+$E$42	=G287+2	=E288+$E$40	=G287	=I288+1	=IF(C288=$A$60,"STOP","")
=A288+1	=C288	=B289+$E$42+$E$42	=D288+$E$40+$E$40	=D288	=B289+$E$42	=G288+2	=E289+$E$40	=G288	=I289+1	=IF(C289=$A$60,"STOP","")
=A289+1	=C289	=B290+$E$42+$E$42	=D289+$E$40+$E$40	=D289	=B290+$E$42	=G289+2	=E290+$E$40	=G289	=I290+1	=IF(C290=$A$60,"STOP","")
=A290+1	=C290	=B291+$E$42+$E$42	=D290+$E$40+$E$40	=D290	=B291+$E$42	=G290+2	=E291+$E$40	=G290	=I291+1	=IF(C291=$A$60,"STOP","")
=A291+1	=C291	=B292+$E$42+$E$42	=D291+$E$40+$E$40	=D291	=B292+$E$42	=G291+2	=E292+$E$40	=G291	=I292+1	=IF(C292=$A$60,"STOP","")
=A292+1	=C292	=B293+$E$42+$E$42	=D292+$E$40+$E$40	=D292	=B293+$E$42	=G292+2	=E293+$E$40	=G292	=I293+1	=IF(C293=$A$60,"STOP","")
=A293+1	=C293	=B294+$E$42+$E$42	=D293+$E$40+$E$40	=D293	=B294+$E$42	=G293+2	=E294+$E$40	=G293	=I294+1	=IF(C294=$A$60,"STOP","")
=A294+1	=C294	=B295+$E$42+$E$42	=D294+$E$40+$E$40	=D294	=B295+$E$42	=G294+2	=E295+$E$40	=G294	=I295+1	=IF(C295=$A$60,"STOP","")
=A295+1	=C295	=B296+$E$42+$E$42	=D295+$E$40+$E$40	=D295	=B296+$E$42	=G295+2	=E296+$E$40	=G295	=I296+1	=IF(C296=$A$60,"STOP","")
=A296+1	=C296	=B297+$E$42+$E$42	=D296+$E$40+$E$40	=D296	=B297+$E$42	=G296+2	=E297+$E$40	=G296	=I297+1	=IF(C297=$A$60,"STOP","")
=A297+1	=C297	=B298+$E$42+$E$42	=D297+$E$40+$E$40	=D297	=B298+$E$42	=G297+2	=E298+$E$40	=G297	=I298+1	=IF(C298=$A$60,"STOP","")
=A298+1	=C298	=B299+$E$42+$E$42	=D298+$E$40+$E$40	=D298	=B299+$E$42	=G298+2	=E299+$E$40	=G298	=I299+1	=IF(C299=$A$60,"STOP","")
=A299+1	=C299	=B300+$E$42+$E$42	=D299+$E$40+$E$40	=D299	=B300+$E$42	=G299+2	=E300+$E$40	=G299	=I300+1	=IF(C300=$A$60,"STOP","")
=A300+1	=C300	=B301+$E$42+$E$42	=D300+$E$40+$E$40	=D300	=B301+$E$42	=G300+2	=E301+$E$40	=G300	=I301+1	=IF(C301=$A$60,"STOP","")
=A301+1	=C301	=B302+$E$42+$E$42	=D301+$E$40+$E$40	=D301	=B302+$E$42	=G301+2	=E302+$E$40	=G301	=I302+1	=IF(C302=$A$60,"STOP","")
=A302+1	=C302	=B303+$E$42+$E$42	=D302+$E$40+$E$40	=D302	=B303+$E$42	=G302+2	=E303+$E$40	=G302	=I303+1	=IF(C303=$A$60,"STOP","")
=A303+1	=C303	=B304+$E$42+$E$42	=D303+$E$40+$E$40	=D303	=B304+$E$42	=G303+2	=E304+$E$40	=G303	=I304+1	=IF(C304=$A$60,"STOP","")
=A304+1	=C304	=B305+$E$42+$E$42	=D304+$E$40+$E$40	=D304	=B305+$E$42	=G304+2	=E305+$E$40	=G304	=I305+1	=IF(C305=$A$60,"STOP","")
=A305+1	=C305	=B306+$E$42+$E$42	=D305+$E$40+$E$40	=D305	=B306+$E$42	=G305+2	=E306+$E$40	=G305	=I306+1	=IF(C306=$A$60,"STOP","")
=A306+1	=C306	=B307+$E$42+$E$42	=D306+$E$40+$E$40	=D306	=B307+$E$42	=G306+2	=E307+$E$40	=G306	=I307+1	=IF(C307=$A$60,"STOP","")
=A307+1	=C307	=B308+$E$42+$E$42	=D307+$E$40+$E$40	=D307	=B308+$E$42	=G307+2	=E308+$E$40	=G307	=I308+1	=IF(C308=$A$60,"STOP","")
=A308+1	=C308	=B309+$E$42+$E$42	=D308+$E$40+$E$40	=D308	=B309+$E$42	=G308+2	=E309+$E$40	=G308	=I309+1	=IF(C309=$A$60,"STOP","")
=A309+1	=C309	=B310+$E$42+$E$42	=D309+$E$40+$E$40	=D309	=B310+$E$42	=G309+2	=E310+$E$40	=G309	=I310+1	=IF(C310=$A$60,"STOP","")
=A310+1	=C310	=B311+$E$42+$E$42	=D310+$E$40+$E$40	=D310	=B311+$E$42	=G310+2	=E311+$E$40	=G310	=I311+1	=IF(C311=$A$60,"STOP","")
=A311+1	=C311	=B312+$E$42+$E$42	=D311+$E$40+$E$40	=D311	=B312+$E$42	=G311+2	=E312+$E$40	=G311	=I312+1	=IF(C312=$A$60,"STOP","")
=A312+1	=C312	=B313+$E$42+$E$42	=D312+$E$40+$E$40	=D312	=B313+$E$42	=G312+2	=E313+$E$40	=G312	=I313+1	=IF(C313=$A$60,"STOP","")
*ELSET	ELSET=STITCHMID	GENERATE								
=A251	=A313	1								

**										
**STITCHRT										
**										
*ELEMENT	TYPE=S9R5									
=A251+E36	=A60	=B320+E42+E42	=E320+E40+E40	=E251+2*E36*E40	=B320+E42	=J313+3	=E320+E40	=G320-2	=I320+1	=IF(C320=$A$62,"STOP","")
=A320+1	=C320	=B321+$E$42+$E$42	=D320+$E$40+$E$40	=D320	=B321+$E$42	=G320+2	=E321+$E$40	=G320	=I321+1	=IF(C321=$A$62,"STOP","")
=A321+1	=C321	=B322+$E$42+$E$42	=D321+$E$40+$E$40	=D321	=B322+$E$42	=G321+2	=E322+$E$40	=G321	=I322+1	=IF(C322=$A$62,"STOP","")
=A322+1	=C322	=B323+$E$42+$E$42	=D322+$E$40+$E$40	=D322	=B323+$E$42	=G322+2	=E323+$E$40	=G322	=I323+1	=IF(C323=$A$62,"STOP","")
=A323+1	=C323	=B324+$E$42+$E$42	=D323+$E$40+$E$40	=D323	=B324+$E$42	=G323+2	=E324+$E$40	=G323	=I324+1	=IF(C324=$A$62,"STOP","")
=A324+1	=C324	=B325+$E$42+$E$42	=D324+$E$40+$E$40	=D324	=B325+$E$42	=G324+2	=E325+$E$40	=G324	=I325+1	=IF(C325=$A$62,"STOP","")
=A325+1	=C325	=B326+$E$42+$E$42	=D325+$E$40+$E$40	=D325	=B326+$E$42	=G325+2	=E326+$E$40	=G325	=I326+1	=IF(C326=$A$62,"STOP","")
=A326+1	=C326	=B327+$E$42+$E$42	=D326+$E$40+$E$40	=D326	=B327+$E$42	=G326+2	=E327+$E$40	=G326	=I327+1	=IF(C327=$A$62,"STOP","")
=A327+1	=C327	=B328+$E$42+$E$42	=D327+$E$40+$E$40	=D327	=B328+$E$42	=G327+2	=E328+$E$40	=G327	=I328+1	=IF(C328=$A$62,"STOP","")
=A328+1	=C328	=B329+$E$42+$E$42	=D328+$E$40+$E$40	=D328	=B329+$E$42	=G328+2	=E329+$E$40	=G328	=I329+1	=IF(C329=$A$62,"STOP","")
=A329+1	=C329	=B330+$E$42+$E$42	=D329+$E$40+$E$40	=D329	=B330+$E$42	=G329+2	=E330+$E$40	=G329	=I330+1	=IF(C330=$A$62,"STOP","")
=A330+1	=C330	=B331+$E$42+$E$42	=D330+$E$40+$E$40	=D330	=B331+$E$42	=G330+2	=E331+$E$40	=G330	=I331+1	=IF(C331=$A$62,"STOP","")
=A331+1	=C331	=B332+$E$42+$E$42	=D331+$E$40+$E$40	=D331	=B332+$E$42	=G331+2	=E332+$E$40	=G331	=I332+1	=IF(C332=$A$62,"STOP","")
=A332+1	=C332	=B333+$E$42+$E$42	=D332+$E$40+$E$40	=D332	=B333+$E$42	=G332+2	=E333+$E$40	=G332	=I333+1	=IF(C333=$A$62,"STOP","")
=A333+1	=C333	=B334+$E$42+$E$42	=D333+$E$40+$E$40	=D333	=B334+$E$42	=G333+2	=E334+$E$40	=G333	=I334+1	=IF(C334=$A$62,"STOP","")
=A334+1	=C334	=B335+$E$42+$E$42	=D334+$E$40+$E$40	=D334	=B335+$E$42	=G334+2	=E335+$E$40	=G334	=I335+1	=IF(C335=$A$62,"STOP","")
=A335+1	=C335	=B336+$E$42+$E$42	=D335+$E$40+$E$40	=D335	=B336+$E$42	=G335+2	=E336+$E$40	=G335	=I336+1	=IF(C336=$A$62,"STOP","")
=A336+1	=C336	=B337+$E$42+$E$42	=D336+$E$40+$E$40	=D336	=B337+$E$42	=G336+2	=E337+$E$40	=G336	=I337+1	=IF(C337=$A$62,"STOP","")
=A337+1	=C337	=B338+$E$42+$E$42	=D337+$E$40+$E$40	=D337	=B338+$E$42	=G337+2	=E338+$E$40	=G337	=I338+1	=IF(C338=$A$62,"STOP","")
=A338+1	=C338	=B339+$E$42+$E$42	=D338+$E$40+$E$40	=D338	=B339+$E$42	=G338+2	=E339+$E$40	=G338	=I339+1	=IF(C339=$A$62,"STOP","")
=A339+1	=C339	=B340+$E$42+$E$42	=D339+$E$40+$E$40	=D339	=B340+$E$42	=G339+2	=E340+$E$40	=G339	=I340+1	=IF(C340=$A$62,"STOP","")
=A340+1	=C340	=B341+$E$42+$E$42	=D340+$E$40+$E$40	=D340	=B341+$E$42	=G340+2	=E341+$E$40	=G340	=I341+1	=IF(C341=$A$62,"STOP","")
=A341+1	=C341	=B342+$E$42+$E$42	=D341+$E$40+$E$40	=D341	=B342+$E$42	=G341+2	=E342+$E$40	=G341	=I342+1	=IF(C342=$A$62,"STOP","")
=A342+1	=C342	=B343+$E$42+$E$42	=D342+$E$40+$E$40	=D342	=B343+$E$42	=G342+2	=E343+$E$40	=G342	=I343+1	=IF(C343=$A$62,"STOP","")
=A343+1	=C343	=B344+$E$42+$E$42	=D343+$E$40+$E$40	=D343	=B344+$E$42	=G343+2	=E344+$E$40	=G343	=I344+1	=IF(C344=$A$62,"STOP","")
=A344+1	=C344	=B345+$E$42+$E$42	=D344+$E$40+$E$40	=D344	=B345+$E$42	=G344+2	=E345+$E$40	=G344	=I345+1	=IF(C345=$A$62,"STOP","")
=A345+1	=C345	=B346+$E$42+$E$42	=D345+$E$40+$E$40	=D345	=B346+$E$42	=G345+2	=E346+$E$40	=G345	=I346+1	=IF(C346=$A$62,"STOP","")
=A346+1	=C346	=B347+$E$42+$E$42	=D346+$E$40+$E$40	=D346	=B347+$E$42	=G346+2	=E347+$E$40	=G346	=I347+1	=IF(C347=$A$62,"STOP","")
=A347+1	=C347	=B348+$E$42+$E$42	=D347+$E$40+$E$40	=D347	=B348+$E$42	=G347+2	=E348+$E$40	=G347	=I348+1	=IF(C348=$A$62,"STOP","")
=A348+1	=C348	=B349+$E$42+$E$42	=D348+$E$40+$E$40	=D348	=B349+$E$42	=G348+2	=E349+$E$40	=G348	=I349+1	=IF(C349=$A$62,"STOP","")
=A349+1	=C349	=B350+$E$42+$E$42	=D349+$E$40+$E$40	=D349	=B350+$E$42	=G349+2	=E350+$E$40	=G349	=I350+1	=IF(C350=$A$62,"STOP","")
=A350+1	=C350	=B351+$E$42+$E$42	=D350+$E$40+$E$40	=D350	=B351+$E$42	=G350+2	=E351+$E$40	=G350	=I351+1	=IF(C351=$A$62,"STOP","")
=A351+1	=C351	=B352+$E$42+$E$42	=D351+$E$40+$E$40	=D351	=B352+$E$42	=G351+2	=E352+$E$40	=G351	=I352+1	=IF(C352=$A$62,"STOP","")
=A352+1	=C352	=B353+$E$42+$E$42	=D352+$E$40+$E$40	=D352	=B353+$E$42	=G352+2	=E353+$E$40	=G352	=I353+1	=IF(C353=$A$62,"STOP","")
=A353+1	=C353	=B354+$E$42+$E$42	=D353+$E$40+$E$40	=D353	=B354+$E$42	=G353+2	=E354+$E$40	=G353	=I354+1	=IF(C354=$A$62,"STOP","")
=A354+1	=C354	=B355+$E$42+$E$42	=D354+$E$40+$E$40	=D354	=B355+$E$42	=G354+2	=E355+$E$40	=G354	=I355+1	=IF(C355=$A$62,"STOP","")
=A355+1	=C355	=B356+$E$42+$E$42	=D355+$E$40+$E$40	=D355	=B356+$E$42	=G355+2	=E356+$E$40	=G355	=I356+1	=IF(C356=$A$62,"STOP","")
=A356+1	=C356	=B357+$E$42+$E$42	=D356+$E$40+$E$40	=D356	=B357+$E$42	=G356+2	=E357+$E$40	=G356	=I357+1	=IF(C357=$A$62,"STOP","")
=A357+1	=C357	=B358+$E$42+$E$42	=D357+$E$40+$E$40	=D357	=B358+$E$42	=G357+2	=E358+$E$40	=G357	=I358+1	=IF(C358=$A$62,"STOP","")
=A358+1	=C358	=B359+$E$42+$E$42	=D358+$E$40+$E$40	=D358	=B359+$E$42	=G358+2	=E359+$E$40	=G358	=I359+1	=IF(C359=$A$62,"STOP","")
=A359+1	=C359	=B360+$E$42+$E$42	=D359+$E$40+$E$40	=D359	=B360+$E$42	=G359+2	=E360+$E$40	=G359	=I360+1	=IF(C360=$A$62,"STOP","")
=A360+1	=C360	=B361+$E$42+$E$42	=D360+$E$40+$E$40	=D360	=B361+$E$42	=G360+2	=E361+$E$40	=G360	=I361+1	=IF(C361=$A$62,"STOP","")
=A361+1	=C361	=B362+$E$42+$E$42	=D361+$E$40+$E$40	=D361	=B362+$E$42	=G361+2	=E362+$E$40	=G361	=I362+1	=IF(C362=$A$62,"STOP","")
=A362+1	=C362	=B363+$E$42+$E$42	=D362+$E$40+$E$40	=D362	=B363+$E$42	=G362+2	=E363+$E$40	=G362	=I363+1	=IF(C363=$A$62,"STOP","")
=A363+1	=C363	=B364+$E$42+$E$42	=D363+$E$40+$E$40	=D363	=B364+$E$42	=G363+2	=E364+$E$40	=G363	=I364+1	=IF(C364=$A$62,"STOP","")
=A364+1	=C364	=B365+$E$42+$E$42	=D364+$E$40+$E$40	=D364	=B365+$E$42	=G364+2	=E365+$E$40	=G364	=I365+1	=IF(C365=$A$62,"STOP","")
=A365+1	=C365	=B366+$E$42+$E$42	=D365+$E$40+$E$40	=D365	=B366+$E$42	=G365+2	=E366+$E$40	=G365	=I366+1	=IF(C366=$A$62,"STOP","")
=A366+1	=C366	=B367+$E$42+$E$42	=D366+$E$40+$E$40	=D366	=B367+$E$42	=G366+2	=E367+$E$40	=G366	=I367+1	=IF(C367=$A$62,"STOP","")
=A367+1	=C367	=B368+$E$42+$E$42	=D367+$E$40+$E$40	=D367	=B368+$E$42	=G367+2	=E368+$E$40	=G367	=I368+1	=IF(C368=$A$62,"STOP","")
=A368+1	=C368	=B369+$E$42+$E$42	=D368+$E$40+$E$40	=D368	=B369+$E$42	=G368+2	=E369+$E$40	=G368	=I369+1	=IF(C369=$A$62,"STOP","")
=A369+1	=C369	=B370+$E$42+$E$42	=D369+$E$40+$E$40	=D369	=B370+$E$42	=G369+2	=E370+$E$40	=G369	=I370+1	=IF(C370=$A$62,"STOP","")
=A370+1	=C370	=B371+$E$42+$E$42	=D370+$E$40+$E$40	=D370	=B371+$E$42	=G370+2	=E371+$E$40	=G370	=I371+1	=IF(C371=$A$62,"STOP","")
=A371+1	=C371	=B372+$E$42+$E$42	=D371+$E$40+$E$40	=D371	=B372+$E$42	=G371+2	=E372+$E$40	=G371	=I372+1	=IF(C372=$A$62,"STOP","")
=A372+1	=C372	=B373+$E$42+$E$42	=D372+$E$40+$E$40	=D372	=B373+$E$42	=G372+2	=E373+$E$40	=G372	=I373+1	=IF(C373=$A$62,"STOP","")
=A373+1	=C373	=B374+$E$42+$E$42	=D373+$E$40+$E$40	=D373	=B374+$E$42	=G373+2	=E374+$E$40	=G373	=I374+1	=IF(C374=$A$62,"STOP","")
=A374+1	=C374	=B375+$E$42+$E$42	=D374+$E$40+$E$40	=D374	=B375+$E$42	=G374+2	=E375+$E$40	=G374	=I375+1	=IF(C375=$A$62,"STOP","")
=A375+1	=C375	=B376+$E$42+$E$42	=D375+$E$40+$E$40	=D375	=B376+$E$42	=G375+2	=E376+$E$40	=G375	=I376+1	=IF(C376=$A$62,"STOP","")
=A376+1	=C376	=B377+$E$42+$E$42	=D376+$E$40+$E$40	=D376	=B377+$E$42	=G376+2	=E377+$E$40	=G376	=I377+1	=IF(C377=$A$62,"STOP","")
=A377+1	=C377	=B378+$E$42+$E$42	=D377+$E$40+$E$40	=D377	=B378+$E$42	=G377+2	=E378+$E$40	=G377	=I378+1	=IF(C378=$A$62,"STOP","")
=A378+1	=C378	=B379+$E$42+$E$42	=D378+$E$40+$E$40	=D378	=B379+$E$42	=G378+2	=E379+$E$40	=G378	=I379+1	=IF(C379=$A$62,"STOP","")
=A379+1	=C379	=B380+$E$42+$E$42	=D379+$E$40+$E$40	=D379	=B380+$E$42	=G379+2	=E380+$E$40	=G379	=I380+1	=IF(C380=$A$62,"STOP","")
=A380+1	=C380	=B381+$E$42+$E$42	=D380+$E$40+$E$40	=D380	=B381+$E$42	=G380+2	=E381+$E$40	=G380	=I381+1	=IF(C381=$A$62,"STOP","")
=A381+1	=C381	=B382+$E$42+$E$42	=D381+$E$40+$E$40	=D381	=B382+$E$42	=G381+2	=E382+$E$40	=G381	=I382+1	=IF(C382=$A$62,"STOP","")
*ELSET	ELSET=STITCHRT	GENERATE								
=A320	=A382	1								

**			
**SECTION PROPERTIES			
**			
*SHELL SECTION	ELSET=FLANGELT	MATERIAL=RIGID	
=C23			
*SHELL SECTION	ELSET=WEBLT	MATERIAL=RIGID	
=C24			
*SHELL SECTION	ELSET=STITCHLT	MATERIAL=RIGID	
=C24			
*SHELL SECTION	ELSET=FLANGERT	MATERIAL=RIGID	
=C23			
*SHELL SECTION	ELSET=WEBRT	MATERIAL=RIGID	
=C24			
*SHELL SECTION	ELSET=STITCHRT	MATERIAL=RIGID	
=C24			
*SHELL SECTION	ELSET=FLANGEMID	MATERIAL=STEEL	
=C23			
*SHELL SECTION	ELSET=WEBMID	MATERIAL=STEEL	
=C24			
*SHELL SECTION	ELSET=STITCHMID	MATERIAL=STEEL	
=C24			
**			
**MATERIAL PROPERTIES			
**			
*MATERIAL	NAME=RIGID		
*ELASTIC			
=F24	0.3		
*MATERIAL	NAME=STEEL		
*ELASTIC			
=F19	0.3		
*PLASTIC			
=F20	0		
=A416+1.345	0.00922948		
=A416+25	0.0557238		
=A416+30	0.090034		
**			
**BOUNDARY CONDITIONS			
**			
*BOUNDARY			
FLPINLT	1		
FLPINLT	2		
FLPINLT	3		
FLPINRT	2		
FLPINRT	3		
WEBPINLT	2		
WEBPINRT	2		
MIDPINLT	2		
MIDPINRT	2		
**			
**ANALYSIS	INPUT FILE		
**			
*STEP			
*BUCKLE			
10		20	80
*CLOAD			
LTLOAD	3	1	
RTLOAD	3	1	
*RESTART	WRITE	FREQUENCY=1	
*NODE FILE	LAST MODE=1	GLOBAL=YES	
U			
*ELPRINT	FREQUENCY=0		
*END STEP			
**			
**ANALYSIS	MATERIAL PROPERTIES		
**			
*IMPERFECTION	FILE=	=C3	STEP=1
1	=C19/1000		
*STEP	NLGEOM	INC=50	
*STATIC	RIKS		
0.001	1		
*CLOAD			
LTLOAD	3	1	
RTLOAD	3	1	
*RESTART	WRITE	FREQUENCY=1	
*END STEP			

Filename var2_1.25

*Heading
alter tw while bf/d=2.0
RIGID ENDS
S9R5 ELEMENTS
APPROXIMATELY 1" ELEMENTS
ACTUAL WTEE DIMENSIONS
**
**INITIAL CONDITIONS
**

INPUT VARIBLES

	INCHES	STEEL	KSI
Lb=	176.573	E=	29000
L=	529.719	Fy=	50
bf=	28	v=	0.3
d=	14		
tf=	1.523	RIGID	
tw=	1.25	E=	290000

NUMBER OF ELEMENTS IN FLANGE	10	THIS NUMBER CAN BE ALTERED		
NUMBER OF ELEMENTS IN LENGTH	63.06179			
FLANGE ELEMENT SIZE	2.8		midpoint	3981
LENGTH ELEMENT SIZE	2.802746			
WEB ELEMENT SIZE	1.4125			

MESH SETUP

EL FL	10	10	THIS SHOULD BE EVEN
EL Lb	63	63	
EL WB	8.91150442	9	
STITCH	1.2875	1.288	
FLANGE LENGTH INC		21	
FLANGE INC		20	
WEB LENGTH INC		19	
WEB INC		18	

INITIAL COORIDINATES

*NODE

1	0	0	0	
21	0	28	0	
2647	176.573	0	0	
2667	176.573	28	0	
5293	353.146	0	0	
5313	353.146	28	0	
7939	529.719	0	0	
7959	529.719	28	0	
7960	0	14	-14.0005	
7978	0	14	-1.288	
10354	176.573	14	-14.0005	
10372	176.573	14	-1.288	
12748	353.146	14	-14.0005	
12766	353.146	14	-1.288	
15142	529.719	14	-14.0005	
15160	529.719	14	-1.288	
51000	0	14	-0.644	First node of stitch, start at even number,
51378	529.719	14	-0.644	must be greater than last assigned node

```
**
**NODE DEFINITION
**
*NGEN           NSET=BFLANGELT
              1               2647          21
*NGEN           NSET=TFLANGELT
             21               2667          21
*NGEN           NSET=BFLANGEMID
           2647               5293          21
*NGEN           NSET=TFLANGEMID
           2667               5313          21
*NGEN           NSET=BFLANGERT
           5293               7939          21
*NGEN           NSET=TFLANGERT
           5313               7959          21
*NGEN           NSET=BWEBLT
           7960              10354          19
*NGEN           NSET=TWEBLT
           7978              10372          19
*NGEN           NSET=BWEBMID
          10354              12748          19
*NGEN           NSET=TWEBMID
          10372              12766          19
*NGEN           NSET=BWEBRT
          12748              15142          19
*NGEN           NSET=TWEBRT
          12766              15160          19
*NGEN           NSET=STITCH
          51000              51378           1

**
**FILL NODES
**

*NFILL          NSET=FLANGELT
BFLANGELT       TFLANGELT                   20
*NFILL          NSET=FLANGEMID
BFLANGEMID      TFLANGEMID                  20
*NFILL          NSET=FLANGERT
BFLANGERT       TFLANGERT                   20
*NFILL          NSET=WEBLT
BWEBLT          TWEBLT                      18
*NFILL          NSET=WEBMID
BWEBMID         TWEBMID                     18
*NFILL          NSET=WEBRT
BWEBRT          TWEBRT                      18

**
**CONSTRAINT SETS
**

*NSET           NSET=FLPINLT        GENERATE
              1                 21           1
*NSET           NSET=FLPINRT        GENERATE
           7939               7959           1
*NSET           NSET=WEBPINLT       GENERATE
           7960               7978           1
*NSET           NSET=WEBPINRT       GENERATE
          15142              15160           1
*NSET           NSET=MIDPINLT       GENERATE
          10354              10372           1
*NSET           NSET=MIDPINRT       GENERATE
          12748              12766           1
*NSET           NSET=LTLOAD         GENERATE
           2647               2667           1
*NSET           NSET=RTLOAD         GENERATE
           5293               5313           1
```

```
**
**FLANGELT
**
             MASTER ELEMENT
*ELEMENT     TYPE=S9R5
          1              1     43     45      3     22     44     24      2     23
             GENERATE ELEMENT SET
*ELGEN       ELSET=FLANGELT
          1             63     42      1     10      2    189
**
**FLANGEMID
**
*ELEMENT     TYPE=S9R5
         64           2647   2689   2691   2649   2668   2690   2670   2648   2669
*ELGEN       ELSET=FLANGEMID
         64             63     42      1     10      2    189
**
**FLANGERT
**
*ELEMENT     TYPE=S9R5
        127           5293   5335   5337   5295   5314   5336   5316   5294   5315
*ELGEN       ELSET=FLANGERT
        127             63     42      1     10      2    189
**
**WEBLT
**
*ELEMENT     TYPE=S9R5
       1891           7960   7998   8000   7962   7979   7999   7981   7961   7980
*ELGEN       ELSET=WEBLT
       1891             63     38      1      9      2    189
**
**WEBMID
**
*ELEMENT     TYPE=S9R5
       1954          10354  10392  10394  10356  10373  10393  10375  10355  10374
*ELGEN       ELSET=WEBMID
       1954             63     38      1      9      2    189
**
**WEBRT
**
*ELEMENT     TYPE=S9R5
       2017          12748  12786  12788  12750  12767  12787  12769  12749  12768
*ELGEN       ELSET=WEBRT
       2017             63     38      1      9      2    189
```

**											
**STITCHLT											
**											
*ELEMENT	TYPE=S9R5										
3592	7978	8016	53	11	7997	51002	32	51000	51001		
3593	8016	8054	95	53	8035	51004	74	51002	51003		
3594	8054	8092	137	95	8073	51006	116	51004	51005		
3595	8092	8130	179	137	8111	51008	158	51006	51007		
3596	8130	8168	221	179	8149	51010	200	51008	51009		
3597	8168	8206	263	221	8187	51012	242	51010	51011		
3598	8206	8244	305	263	8225	51014	284	51012	51013		
3599	8244	8282	347	305	8263	51016	326	51014	51015		
3600	8282	8320	389	347	8301	51018	368	51016	51017		
3601	8320	8358	431	389	8339	51020	410	51018	51019		
3602	8358	8396	473	431	8377	51022	452	51020	51021		
3603	8396	8434	515	473	8415	51024	494	51022	51023		
3604	8434	8472	557	515	8453	51026	536	51024	51025		
3605	8472	8510	599	557	8491	51028	578	51026	51027		
3606	8510	8548	641	599	8529	51030	620	51028	51029		
3607	8548	8586	683	641	8567	51032	662	51030	51031		
3608	8586	8624	725	683	8605	51034	704	51032	51033		
3609	8624	8662	767	725	8643	51036	746	51034	51035		
3610	8662	8700	809	767	8681	51038	788	51036	51037		
3611	8700	8738	851	809	8719	51040	830	51038	51039		
3612	8738	8776	893	851	8757	51042	872	51040	51041		
3613	8776	8814	935	893	8795	51044	914	51042	51043		
3614	8814	8852	977	935	8833	51046	956	51044	51045		
3615	8852	8890	1019	977	8871	51048	998	51046	51047		
3616	8890	8928	1061	1019	8909	51050	1040	51048	51049		
3617	8928	8966	1103	1061	8947	51052	1082	51050	51051		
3618	8966	9004	1145	1103	8985	51054	1124	51052	51053		
3619	9004	9042	1187	1145	9023	51056	1166	51054	51055		
3620	9042	9080	1229	1187	9061	51058	1208	51056	51057		
3621	9080	9118	1271	1229	9099	51060	1250	51058	51059		
3622	9118	9156	1313	1271	9137	51062	1292	51060	51061		
3623	9156	9194	1355	1313	9175	51064	1334	51062	51063		
3624	9194	9232	1397	1355	9213	51066	1376	51064	51065		
3625	9232	9270	1439	1397	9251	51068	1418	51066	51067		
3626	9270	9308	1481	1439	9289	51070	1460	51068	51069		
3627	9308	9346	1523	1481	9327	51072	1502	51070	51071		
3628	9346	9384	1565	1523	9365	51074	1544	51072	51073		
3629	9384	9422	1607	1565	9403	51076	1586	51074	51075		
3630	9422	9460	1649	1607	9441	51078	1628	51076	51077		
3631	9460	9498	1691	1649	9479	51080	1670	51078	51079		
3632	9498	9536	1733	1691	9517	51082	1712	51080	51081		
3633	9536	9574	1775	1733	9555	51084	1754	51082	51083		
3634	9574	9612	1817	1775	9593	51086	1796	51084	51085		
3635	9612	9650	1859	1817	9631	51088	1838	51086	51087		
3636	9650	9688	1901	1859	9669	51090	1880	51088	51089		
3637	9688	9726	1943	1901	9707	51092	1922	51090	51091		
3638	9726	9764	1985	1943	9745	51094	1964	51092	51093		
3639	9764	9802	2027	1985	9783	51096	2006	51094	51095		
3640	9802	9840	2069	2027	9821	51098	2048	51096	51097		
3641	9840	9878	2111	2069	9859	51100	2090	51098	51099		
3642	9878	9916	2153	2111	9897	51102	2132	51100	51101		
3643	9916	9954	2195	2153	9935	51104	2174	51102	51103		
3644	9954	9992	2237	2195	9973	51106	2216	51104	51105		
3645	9992	10030	2279	2237	10011	51108	2258	51106	51107		
3646	10030	10068	2321	2279	10049	51110	2300	51108	51109		
3647	10068	10106	2363	2321	10087	51112	2342	51110	51111		
3648	10106	10144	2405	2363	10125	51114	2384	51112	51113		
3649	10144	10182	2447	2405	10163	51116	2426	51114	51115		
3650	10182	10220	2489	2447	10201	51118	2468	51116	51117		
3651	10220	10258	2531	2489	10239	51120	2510	51118	51119		
3652	10258	10296	2573	2531	10277	51122	2552	51120	51121		
3653	10296	10334	2615	2573	10315	51124	2594	51122	51123		
3654	10334	10372	2657	2615	10353	51126	2636	51124	51125	STOP	
*ELSET	ELSET=STITCHLT	GENERATE									
3592	3654	1									

**											
**STITCHMID											
**											
*ELEMENT		TYPE=S9R5									
	3655	10372	10410	2699	2657	10391	51128	2678	51126	51127	
	3656	10410	10448	2741	2699	10429	51130	2720	51128	51129	
	3657	10448	10486	2783	2741	10467	51132	2762	51130	51131	
	3658	10486	10524	2825	2783	10505	51134	2804	51132	51133	
	3659	10524	10562	2867	2825	10543	51136	2846	51134	51135	
	3660	10562	10600	2909	2867	10581	51138	2888	51136	51137	
	3661	10600	10638	2951	2909	10619	51140	2930	51138	51139	
	3662	10638	10676	2993	2951	10657	51142	2972	51140	51141	
	3663	10676	10714	3035	2993	10695	51144	3014	51142	51143	
	3664	10714	10752	3077	3035	10733	51146	3056	51144	51145	
	3665	10752	10790	3119	3077	10771	51148	3098	51146	51147	
	3666	10790	10828	3161	3119	10809	51150	3140	51148	51149	
	3667	10828	10866	3203	3161	10847	51152	3182	51150	51151	
	3668	10866	10904	3245	3203	10885	51154	3224	51152	51153	
	3669	10904	10942	3287	3245	10923	51156	3266	51154	51155	
	3670	10942	10980	3329	3287	10961	51158	3308	51156	51157	
	3671	10980	11018	3371	3329	10999	51160	3350	51158	51159	
	3672	11018	11056	3413	3371	11037	51162	3392	51160	51161	
	3673	11056	11094	3455	3413	11075	51164	3434	51162	51163	
	3674	11094	11132	3497	3455	11113	51166	3476	51164	51165	
	3675	11132	11170	3539	3497	11151	51168	3518	51166	51167	
	3676	11170	11208	3581	3539	11189	51170	3560	51168	51169	
	3677	11208	11246	3623	3581	11227	51172	3602	51170	51171	
	3678	11246	11284	3665	3623	11265	51174	3644	51172	51173	
	3679	11284	11322	3707	3665	11303	51176	3686	51174	51175	
	3680	11322	11360	3749	3707	11341	51178	3728	51176	51177	
	3681	11360	11398	3791	3749	11379	51180	3770	51178	51179	
	3682	11398	11436	3833	3791	11417	51182	3812	51180	51181	
	3683	11436	11474	3875	3833	11455	51184	3854	51182	51183	
	3684	11474	11512	3917	3875	11493	51186	3896	51184	51185	
	3685	11512	11550	3959	3917	11531	51188	3938	51186	51187	
	3686	11550	11588	4001	3959	11569	51190	3980	51188	51189	
	3687	11588	11626	4043	4001	11607	51192	4022	51190	51191	
	3688	11626	11664	4085	4043	11645	51194	4064	51192	51193	
	3689	11664	11702	4127	4085	11683	51196	4106	51194	51195	
	3690	11702	11740	4169	4127	11721	51198	4148	51196	51197	
	3691	11740	11778	4211	4169	11759	51200	4190	51198	51199	
	3692	11778	11816	4253	4211	11797	51202	4232	51200	51201	
	3693	11816	11854	4295	4253	11835	51204	4274	51202	51203	
	3694	11854	11892	4337	4295	11873	51206	4316	51204	51205	
	3695	11892	11930	4379	4337	11911	51208	4358	51206	51207	
	3696	11930	11968	4421	4379	11949	51210	4400	51208	51209	
	3697	11968	12006	4463	4421	11987	51212	4442	51210	51211	
	3698	12006	12044	4505	4463	12025	51214	4484	51212	51213	
	3699	12044	12082	4547	4505	12063	51216	4526	51214	51215	
	3700	12082	12120	4589	4547	12101	51218	4568	51216	51217	
	3701	12120	12158	4631	4589	12139	51220	4610	51218	51219	
	3702	12158	12196	4673	4631	12177	51222	4652	51220	51221	
	3703	12196	12234	4715	4673	12215	51224	4694	51222	51223	
	3704	12234	12272	4757	4715	12253	51226	4736	51224	51225	
	3705	12272	12310	4799	4757	12291	51228	4778	51226	51227	
	3706	12310	12348	4841	4799	12329	51230	4820	51228	51229	
	3707	12348	12386	4883	4841	12367	51232	4862	51230	51231	
	3708	12386	12424	4925	4883	12405	51234	4904	51232	51233	
	3709	12424	12462	4967	4925	12443	51236	4946	51234	51235	
	3710	12462	12500	5009	4967	12481	51238	4988	51236	51237	
	3711	12500	12538	5051	5009	12519	51240	5030	51238	51239	
	3712	12538	12576	5093	5051	12557	51242	5072	51240	51241	
	3713	12576	12614	5135	5093	12595	51244	5114	51242	51243	
	3714	12614	12652	5177	5135	12633	51246	5156	51244	51245	
	3715	12652	12690	5219	5177	12671	51248	5198	51246	51247	
	3716	12690	12728	5261	5219	12709	51250	5240	51248	51249	
	3717	12728	12766	5303	5261	12747	51252	5282	51250	51251	STOP
*ELSET		ELSET=STITCHMID	GENERATE								
	3655	3717	1								

```
**
**STITCHRT
**
*ELEMENT       TYPE=S9R5
      3718      12766   12804   5345   5303   12785   51254   5324   51252   51253
      3719      12804   12842   5387   5345   12823   51256   5366   51254   51255
      3720      12842   12880   5429   5387   12861   51258   5408   51256   51257
      3721      12880   12918   5471   5429   12899   51260   5450   51258   51259
      3722      12918   12956   5513   5471   12937   51262   5492   51260   51261
      3723      12956   12994   5555   5513   12975   51264   5534   51262   51263
      3724      12994   13032   5597   5555   13013   51266   5576   51264   51265
      3725      13032   13070   5639   5597   13051   51268   5618   51266   51267
      3726      13070   13108   5681   5639   13089   51270   5660   51268   51269
      3727      13108   13146   5723   5681   13127   51272   5702   51270   51271
      3728      13146   13184   5765   5723   13165   51274   5744   51272   51273
      3729      13184   13222   5807   5765   13203   51276   5786   51274   51275
      3730      13222   13260   5849   5807   13241   51278   5828   51276   51277
      3731      13260   13298   5891   5849   13279   51280   5870   51278   51279
      3732      13298   13336   5933   5891   13317   51282   5912   51280   51281
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      3735      13412   13450   6059   6017   13431   51288   6038   51286   51287
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      3737      13488   13526   6143   6101   13507   51292   6122   51290   51291
      3738      13526   13564   6185   6143   13545   51294   6164   51292   51293
      3739      13564   13602   6227   6185   13583   51296   6206   51294   51295
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      3741      13640   13678   6311   6269   13659   51300   6290   51298   51299
      3742      13678   13716   6353   6311   13697   51302   6332   51300   51301
      3743      13716   13754   6395   6353   13735   51304   6374   51302   51303
      3744      13754   13792   6437   6395   13773   51306   6416   51304   51305
      3745      13792   13830   6479   6437   13811   51308   6458   51306   51307
      3746      13830   13868   6521   6479   13849   51310   6500   51308   51309
      3747      13868   13906   6563   6521   13887   51312   6542   51310   51311
      3748      13906   13944   6605   6563   13925   51314   6584   51312   51313
      3749      13944   13982   6647   6605   13963   51316   6626   51314   51315
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      3751      14020   14058   6731   6689   14039   51320   6710   51318   51319
      3752      14058   14096   6773   6731   14077   51322   6752   51320   51321
      3753      14096   14134   6815   6773   14115   51324   6794   51322   51323
      3754      14134   14172   6857   6815   14153   51326   6836   51324   51325
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      3757      14248   14286   6983   6941   14267   51332   6962   51330   51331
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      3759      14324   14362   7067   7025   14343   51336   7046   51334   51335
      3760      14362   14400   7109   7067   14381   51338   7088   51336   51337
      3761      14400   14438   7151   7109   14419   51340   7130   51338   51339
      3762      14438   14476   7193   7151   14457   51342   7172   51340   51341
      3763      14476   14514   7235   7193   14495   51344   7214   51342   51343
      3764      14514   14552   7277   7235   14533   51346   7256   51344   51345
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      3766      14590   14628   7361   7319   14609   51350   7340   51348   51349
      3767      14628   14666   7403   7361   14647   51352   7382   51350   51351
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      3771      14780   14818   7571   7529   14799   51360   7550   51358   51359
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      3776      14970   15008   7781   7739   14989   51370   7760   51368   51369
      3777      15008   15046   7823   7781   15027   51372   7802   51370   51371
      3778      15046   15084   7865   7823   15065   51374   7844   51372   51373
      3779      15084   15122   7907   7865   15103   51376   7886   51374   51375
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*ELSET         ELSET=STITCHRT   GENERATE
      3718       3780       1
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            1.25
*SHELL SECTION ELSET=STITCHLT   MATERIAL=RIGID
            1.25
*SHELL SECTION ELSET=FLANGERT   MATERIAL=RIGID
           1.523
*SHELL SECTION ELSET=WEBRT      MATERIAL=RIGID
            1.25
*SHELL SECTION ELSET=STITCHRT   MATERIAL=RIGID
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*SHELL SECTION ELSET=FLANGEMID MATERIAL=STEEL
           1.523
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*SHELL SECTION ELSET=STITCHMID  MATERIAL=STEEL
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*MATERIAL       NAME=RIGID
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*ELASTIC
        2.90E+04                  0.3
*PLASTIC
              50                    0
          51.345           0.00922948
              75            0.0557238
              80             0.090034
**
**BOUNDARY CONDITIONS
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*BOUNDARY
FLPINLT                             1
FLPINLT                             2
FLPINLT                             3
FLPINRT                             2
FLPINRT                             3
WEBPINLT                            2
WEBPINRT                            2
MIDPINLT                            2
MIDPINRT                            2
**
**ANALYSIS      INPUT FILE
**
*STEP
*BUCKLE
              10                                 20         80
*CLOAD
LTLOAD                              3           1
RTLOAD                              3           1
*RESTART        WRITE           FREQUENCY=1
*NODE FILE      LAST MODE=1     GLOBAL=YES
U
*ELPRINT        FREQUENCY=0
*END STEP
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**ANALYSIS      MATERIAL PROPERTIES
**
*IMPERFECTION FILE=             var2_1.25  STEP=1
               1             0.176573
*STEP           NLGEOM          INC=50
*STATIC         RIKS
           0.001                    1
*CLOAD
LTLOAD                              3           1
RTLOAD                              3           1
*RESTART        WRITE           FREQUENCY=1
*END STEP
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*HEADING – SEED IMPERFECTION FILE
ALTER tw WHILE bf/d=2.0
RIGID ENDS
S9R5 ELEMENTS
APPROXIMATELY 1" ELEMENTS
ACTUAL WTEE DIMENSIONS
**
**INITIAL CONDITIONS
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*NODE
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21,0,28,0
2647,176.573,0,0
2667,176.573,28,0
5293,353.146,0,0
5313,353.146,28,0
7939,529.719,0,0
7959,529.719,28,0
7960,0,14,-14.0005
7978,0,14,-1.288
10354,176.573,14,-14.0005
10372,176.573,14,-1.288
12748,353.146,14,-14.0005
12766,353.146,14,-1.288
15142,529.719,14,-14.0005
15160,529.719,14,-1.288
51000,0,14,-0.644
51378,529.719,14,-0.644
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**NODE DEFINITION
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*NGEN,NSET=BFLANGELT
1,2647,21
*NGEN,NSET=TFLANGELT
21,2667,21
*NGEN,NSET=BFLANGEMID
2647,5293,21
*NGEN,NSET=TFLANGEMID
2667,5313,21
*NGEN,NSET=BFLANGERT
5293,7939,21
*NGEN,NSET=TFLANGERT
5313,7959,21
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*NGEN,NSET=BWEBLT
7960,10354,19
*NGEN,NSET=TWEBLT
7978,10372,19
*NGEN,NSET=BWEBMID
10354,12748,19
*NGEN,NSET=TWEBMID
10372,12766,19
*NGEN,NSET=BWEBRT
12748,15142,19
*NGEN,NSET=TWEBRT
12766,15160,19
*NGEN,NSET=STITCH
51000,51378,1
**
**FILL NODES
**
*NFILL,NSET=FLANGELT
BFLANGELT,TFLANGELT,20
*NFILL,NSET=FLANGEMID
BFLANGEMID,TFLANGEMID,20
*NFILL,NSET=FLANGERT
BFLANGERT,TFLANGERT,20
*NFILL,NSET=WEBLT
BWEBLT,TWEBLT,18
*NFILL,NSET=WEBMID
BWEBMID,TWEBMID,18
*NFILL,NSET=WEBRT
BWEBRT,TWEBRT,18
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**CONSTRAINT SETS
**
*NSET,NSET=FLPINLT,GENERATE
1,21,1
*NSET,NSET=FLPINRT,GENERATE
7939,7959,1
*NSET,NSET=WEBPINLT,GENERATE
7960,7978,1
*NSET,NSET=WEBPINRT,GENERATE
15142,15160,1
*NSET,NSET=MIDPINLT,GENERATE
10354,10372,1
*NSET,NSET=MIDPINRT,GENERATE
12748,12766,1
*NSET,NSET=LTLOAD,GENERATE
2647,2667,1
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*NSET,NSET=RTLOAD,GENERATE
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**FLANGELT
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*ELGEN,ELSET=FLANGELT
1,63,42,1,10,2,189
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64,2647,2689,2691,2649,2668,2690,2670,2648,2669
*ELGEN,ELSET=FLANGEMID
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127,5293,5335,5337,5295,5314,5336,5316,5294,5315
*ELGEN,ELSET=FLANGERT
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**WEBLT
**
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*ELGEN,ELSET=WEBLT
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**WEBMID
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1954,10354,10392,10394,10356,10373,10393,10375,10355,10374
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**
**WEBRT
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*ELGEN,ELSET=WEBRT
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3655,3717,1
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3722,12918,12956,5513,5471,12937,51262,5492,51260,51261
3723,12956,12994,5555,5513,12975,51264,5534,51262,51263
3724,12994,13032,5597,5555,13013,51266,5576,51264,51265
3725,13032,13070,5639,5597,13051,51268,5618,51266,51267
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3730,13222,13260,5849,5807,13241,51278,5828,51276,51277
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3733,13336,13374,5975,5933,13355,51284,5954,51282,51283
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3739,13564,13602,6227,6185,13583,51296,6206,51294,51295
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*ELSET,ELSET=STITCHRT,GENERATE
3718,3780,1
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**SECTION PROPERTIES
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1.523
*SHELL SECTION,ELSET=WEBLT,MATERIAL=RIGID
1.25
*SHELL SECTION,ELSET=STITCHLT,MATERIAL=RIGID
1.25
*SHELL SECTION,ELSET=FLANGERT,MATERIAL=RIGID
1.523
*SHELL SECTION,ELSET=WEBRT,MATERIAL=RIGID
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*SHELL SECTION,ELSET=STITCHRT,MATERIAL=RIGID
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*SHELL SECTION,ELSET=FLANGEMID,MATERIAL=STEEL
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*SHELL SECTION,ELSET=WEBMID,MATERIAL=STEEL
1.25
*SHELL SECTION,ELSET=STITCHMID,MATERIAL=STEEL
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**MATERIAL PROPERTIES
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*MATERIAL,NAME=RIGID
*ELASTIC
2.90E+05,0.3
*MATERIAL,NAME=STEEL
*ELASTIC
2.90E+04,0.3
*PLASTIC
50,0
51.345,0.00922948
75,0.0557238
80,0.090034
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**BOUNDARY CONDITIONS
**
*BOUNDARY
FLPINLT,1
FLPINLT,2
FLPINLT,3
FLPINRT,2
FLPINRT,3
WEBPINLT,2
WEBPINRT,2
MIDPINLT,2
MIDPINRT,2
**
**ANALYSIS,INPUT FILE
**
*STEP
*BUCKLE
10,,20,80
*CLOAD
LTLOAD,3,1
RTLOAD,3,1
*RESTART,WRITE,FREQUENCY=1
*NODE FILE,LAST MODE=1,GLOBAL=YES
U
*ELPRINT,FREQUENCY=0
*END STEP
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*HEADING – MATERIAL PROPERTIES FILE
ALTER tw WHILE bf/d=2.0
RIGID ENDS
S9R5 ELEMENTS
APPROXIMATELY 1" ELEMENTS
ACTUAL WTEE DIMENSIONS
**
**INITIAL CONDITIONS
**
*NODE
1,0,0,0
21,0,28,0
2647,176.573,0,0
2667,176.573,28,0
5293,353.146,0,0
5313,353.146,28,0
7939,529.719,0,0
7959,529.719,28,0
7960,0,14,-14.0005
7978,0,14,-1.288
10354,176.573,14,-14.0005
10372,176.573,14,-1.288
12748,353.146,14,-14.0005
12766,353.146,14,-1.288
15142,529.719,14,-14.0005
15160,529.719,14,-1.288
51000,0,14,-0.644
51378,529.719,14,-0.644
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**NODE DEFINITION
**
*NGEN,NSET=BFLANGELT
1,2647,21
*NGEN,NSET=TFLANGELT
21,2667,21
*NGEN,NSET=BFLANGEMID
2647,5293,21
*NGEN,NSET=TFLANGEMID
2667,5313,21
*NGEN,NSET=BFLANGERT
5293,7939,21
*NGEN,NSET=TFLANGERT
5313,7959,21
*NGEN,NSET=BWEBLT
7960,10354,19
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*NGEN,NSET=TWEBLT
7978,10372,19
*NGEN,NSET=BWEBMID
10354,12748,19
*NGEN,NSET=TWEBMID
10372,12766,19
*NGEN,NSET=BWEBRT
12748,15142,19
*NGEN,NSET=TWEBRT
12766,15160,19
*NGEN,NSET=STITCH
51000,51378,1
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**FILL NODES
**
*NFILL,NSET=FLANGELT
BFLANGELT,TFLANGELT,20
*NFILL,NSET=FLANGEMID
BFLANGEMID,TFLANGEMID,20
*NFILL,NSET=FLANGERT
BFLANGERT,TFLANGERT,20
*NFILL,NSET=WEBLT
BWEBLT,TWEBLT,18
*NFILL,NSET=WEBMID
BWEBMID,TWEBMID,18
*NFILL,NSET=WEBRT
BWEBRT,TWEBRT,18
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**CONSTRAINT SETS
**
*NSET,NSET=FLPINLT,GENERATE
1,21,1
*NSET,NSET=FLPINRT,GENERATE
7939,7959,1
*NSET,NSET=WEBPINLT,GENERATE
7960,7978,1
*NSET,NSET=WEBPINRT,GENERATE
15142,15160,1
*NSET,NSET=MIDPINLT,GENERATE
10354,10372,1
*NSET,NSET=MIDPINRT,GENERATE
12748,12766,1
*NSET,NSET=LTLOAD,GENERATE
2647,2667,1
*NSET,NSET=RTLOAD,GENERATE
5293,5313,1
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*ELEMENT ,TYPE=S9R5
1,1,43,45,3,22,44,24,2,23
*ELGEN,ELSET=FLANGELT
1,63,42,1,10,2,189
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**FLANGEMID
**
*ELEMENT,TYPE=S9R5
64,2647,2689,2691,2649,2668,2690,2670,2648,2669
*ELGEN,ELSET=FLANGEMID
64,63,42,1,10,2,189
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**FLANGERT
**
*ELEMENT,TYPE=S9R5
127,5293,5335,5337,5295,5314,5336,5316,5294,5315
*ELGEN,ELSET=FLANGERT
127,63,42,1,10,2,189
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**WEBLT
**
*ELEMENT,TYPE=S9R5
1891,7960,7998,8000,7962,7979,7999,7981,7961,7980
*ELGEN,ELSET=WEBLT
1891,63,38,1,9,2,189
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**WEBMID
**
*ELEMENT,TYPE=S9R5
1954,10354,10392,10394,10356,10373,10393,10375,10355,10374
*ELGEN,ELSET=WEBMID
1954,63,38,1,9,2,189
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**WEBRT
**
*ELEMENT,TYPE=S9R5
2017,12748,12786,12788,12750,12767,12787,12769,12749,12768
*ELGEN,ELSET=WEBRT
2017,63,38,1,9,2,189
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**STITCHLT
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3595,8092,8130,179,137,8111,51008,158,51006,51007
3596,8130,8168,221,179,8149,51010,200,51008,51009
3597,8168,8206,263,221,8187,51012,242,51010,51011
3598,8206,8244,305,263,8225,51014,284,51012,51013
3599,8244,8282,347,305,8263,51016,326,51014,51015
3600,8282,8320,389,347,8301,51018,368,51016,51017
3601,8320,8358,431,389,8339,51020,410,51018,51019
3602,8358,8396,473,431,8377,51022,452,51020,51021
3603,8396,8434,515,473,8415,51024,494,51022,51023
3604,8434,8472,557,515,8453,51026,536,51024,51025
3605,8472,8510,599,557,8491,51028,578,51026,51027
3606,8510,8548,641,599,8529,51030,620,51028,51029
3607,8548,8586,683,641,8567,51032,662,51030,51031
3608,8586,8624,725,683,8605,51034,704,51032,51033
3609,8624,8662,767,725,8643,51036,746,51034,51035
3610,8662,8700,809,767,8681,51038,788,51036,51037
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3612,8738,8776,893,851,8757,51042,872,51040,51041
3613,8776,8814,935,893,8795,51044,914,51042,51043
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3640,9802,9840,2069,2027,9821,51098,2048,51096,51097
3641,9840,9878,2111,2069,9859,51100,2090,51098,51099
3642,9878,9916,2153,2111,9897,51102,2132,51100,51101
3643,9916,9954,2195,2153,9935,51104,2174,51102,51103
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3592,3654,1
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3657,10448,10486,2783,2741,10467,51132,2762,51130,51131
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3717,12728,12766,5303,5261,12747,51252,5282,51250,51251
*ELSET,ELSET=STITCHMID,GENERATE
3655,3717,1
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**STITCHRT
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*ELEMENT,TYPE=S9R5
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*ELSET,ELSET=STITCHRT,GENERATE
3718,3780,1
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**SECTION PROPERTIES
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1.523
*SHELL SECTION,ELSET=WEBLT,MATERIAL=RIGID
1.25
*SHELL SECTION,ELSET=STITCHLT,MATERIAL=RIGID
1.25
*SHELL SECTION,ELSET=FLANGERT,MATERIAL=RIGID
1.523
*SHELL SECTION,ELSET=WEBRT,MATERIAL=RIGID
1.25
*SHELL SECTION,ELSET=STITCHRT,MATERIAL=RIGID
1.25
*SHELL SECTION,ELSET=FLANGEMID,MATERIAL=STEEL
1.523
*SHELL SECTION,ELSET=WEBMID,MATERIAL=STEEL
1.25
*SHELL SECTION,ELSET=STITCHMID,MATERIAL=STEEL
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**MATERIAL PROPERTIES
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*ELASTIC
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*MATERIAL,NAME=STEEL
*ELASTIC
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*PLASTIC
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75,0.0557238
80,0.090034
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**BOUNDARY CONDITIONS
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*BOUNDARY
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FLPINLT,2
FLPINLT,3
FLPINRT,2
FLPINRT,3
WEBPINLT,2
WEBPINRT,2
MIDPINLT,2
MIDPINRT,2
**
**ANALYSIS,MATERIAL PROPERTIES
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*IMPERFECTION,FILE=var2_1.25_imp,STEP=1
1,0.176573
*STEP,NLGEOM,INC=50
*STATIC,RIKS
0.001,1
*CLOAD
LTLOAD,3,1
RTLOAD,3,1
*RESTART,WRITE,FREQUENCY=1
*END STEP
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File used to obtain the reactions at the end of the beam (RF3), rotation at the centerline of the end of the beam (U3), and the overall deflection at the center point of the beam at the bottom of the stem (UR2).

```
read curve, name=load1, variable=RF3, node=1
read curve, name=load2, variable=RF3, node=2
read curve, name=load3, variable=RF3, node=3
read curve, name=load4, variable=RF3, node=4
read curve, name=load5, variable=RF3, node=5
read curve, name=load6, variable=RF3, node=6
read curve, name=load7, variable=RF3, node=7
read curve, name=load8, variable=RF3, node=8
read curve, name=load9, variable=RF3, node=9
read curve, name=load10, variable=RF3, node=10
read curve, name=load11, variable=RF3, node=11
read curve, name=load12, variable=RF3, node=12
read curve, name=load13, variable=RF3, node=13
read curve, name=load14, variable=RF3, node=14
read curve, name=load15, variable=RF3, node=15
read curve, name=load16, variable=RF3, node=16
read curve, name=load17, variable=RF3, node=17
read curve, name=load18, variable=RF3, node=18
read curve, name=load19, variable=RF3, node=19
read curve, name=load20, variable=RF3, node=20
read curve, name=load21, variable=RF3, node=21
read curve, name=defl, variable=U3, node=3981
read curve, name=rot, variable=UR2, node=11
print curve, all curves
```

APPENDIX B

Output From ABAQUS

Upon completion of an analysis of a WTEE beam, employing ABAQUS, the output is analyzed. From this output, the moment versus rotation curves may be plotted, and thus, the rotation capacity calculated. A graph of the moment vs. rotation for each of the cases of b_f / d is shown appendix Section B1.

Illustrative figures from ABAQUS are presented in Section B2. These figures include a typical seed imperfection that is applied to each of the WTEE beams in this research, a typical deflected shape after the WTEE beam has been loaded, and various beams with the von Mises stresses shown through the use of shading.

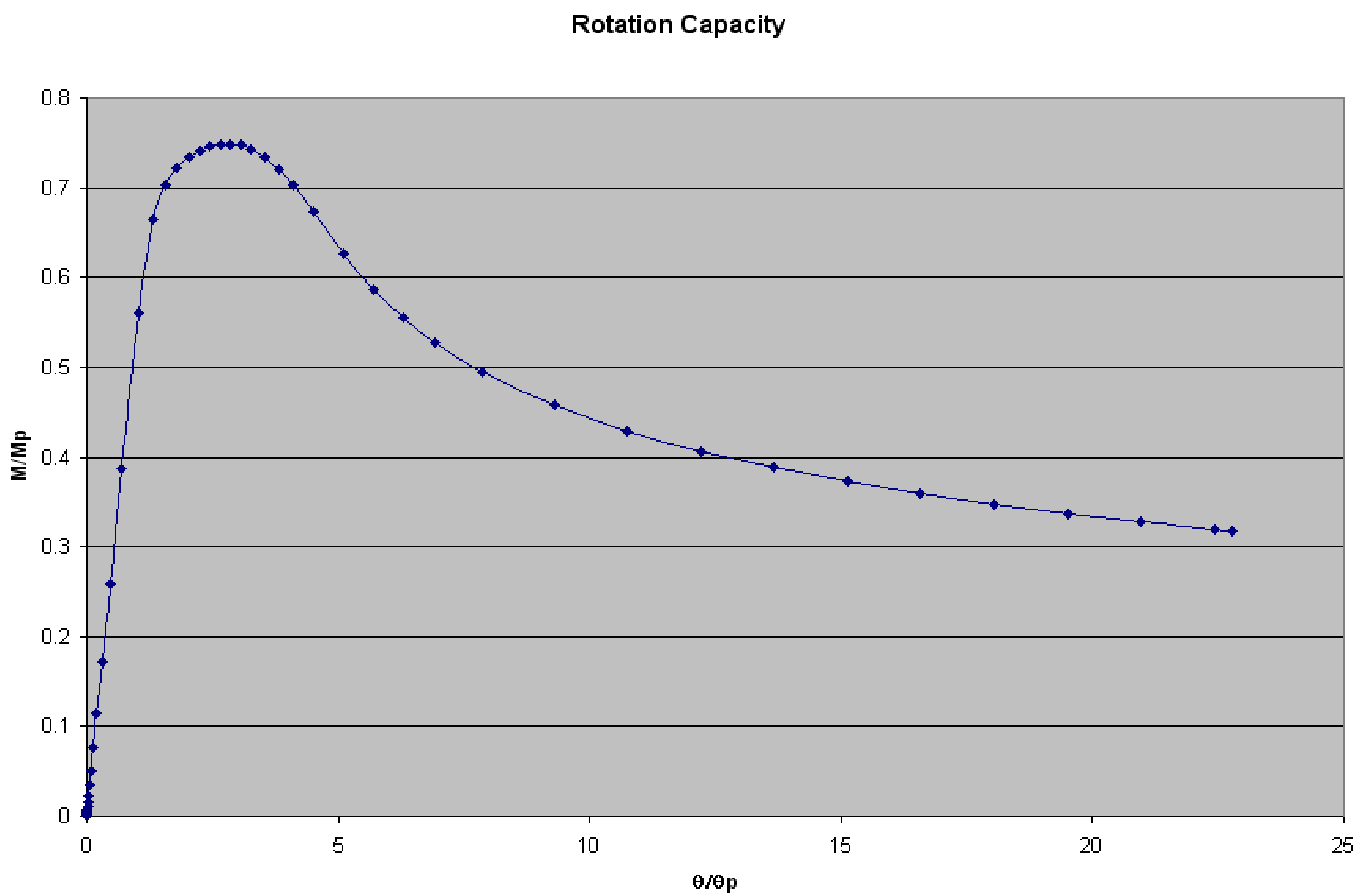

Figure B1 Moment vs. Rotation for WTEE $b_f / d = 0.6$, $t_w = 1.0$”

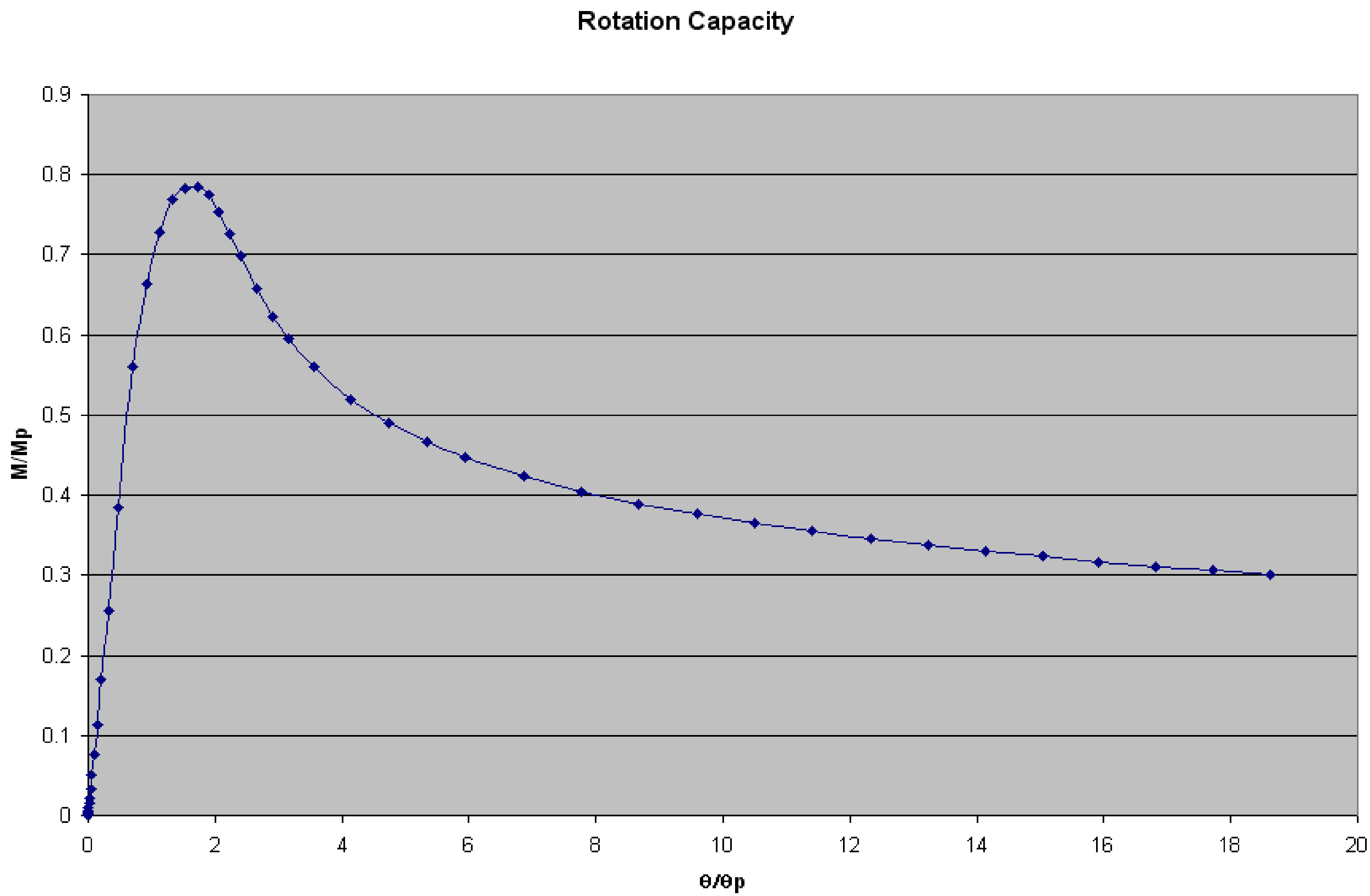

Figure B2 Moment vs. Rotation for WTEE b_f / d =0.8, t_w=1.0”

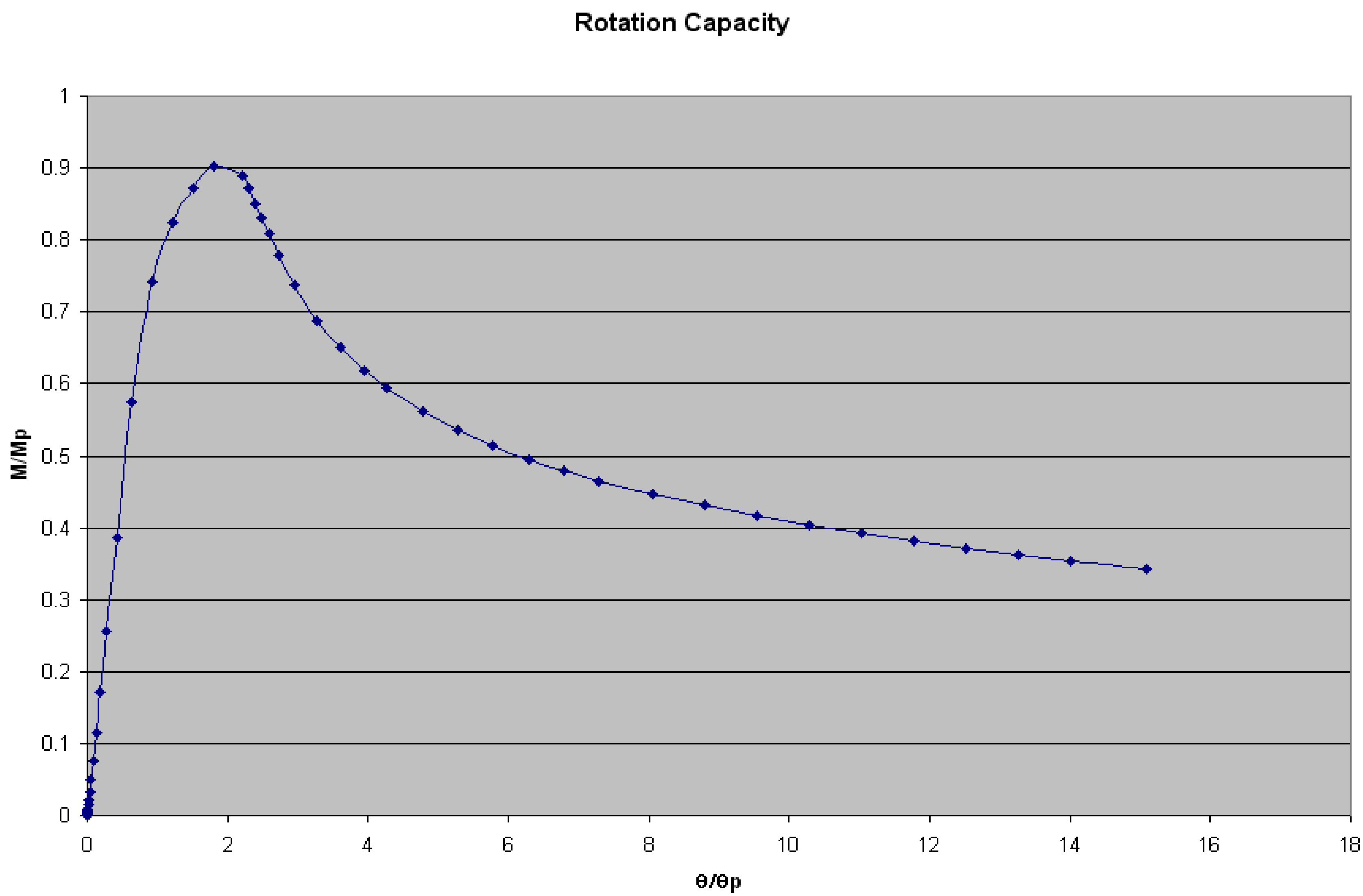

Figure B3 Moment vs. Rotation for WTEE b_f / d =1.0, t_w=1.0”

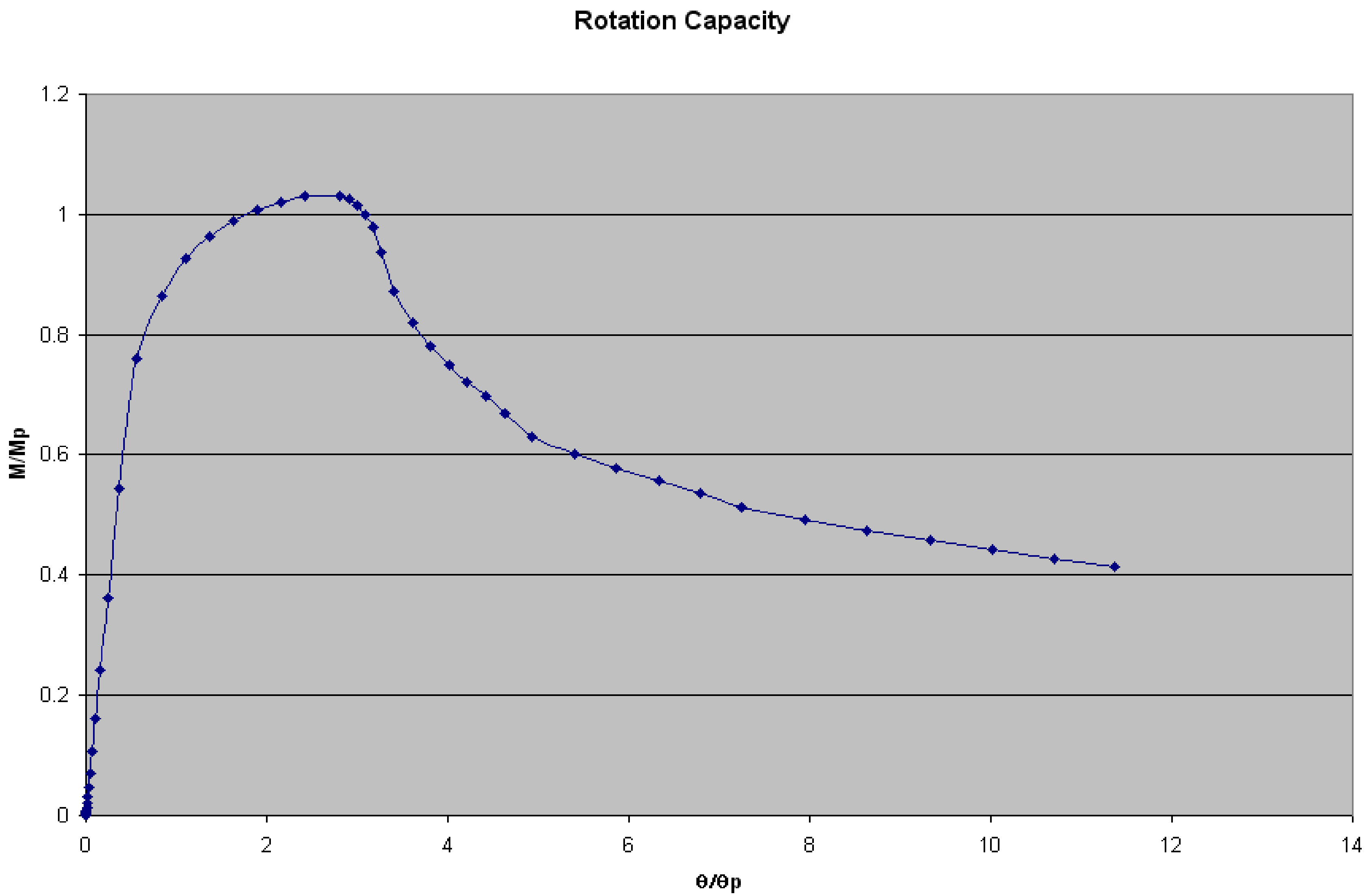

Figure B4 Moment vs. Rotation for WTEE $b_f / d = 1.2$, $t_w = 1.0$"

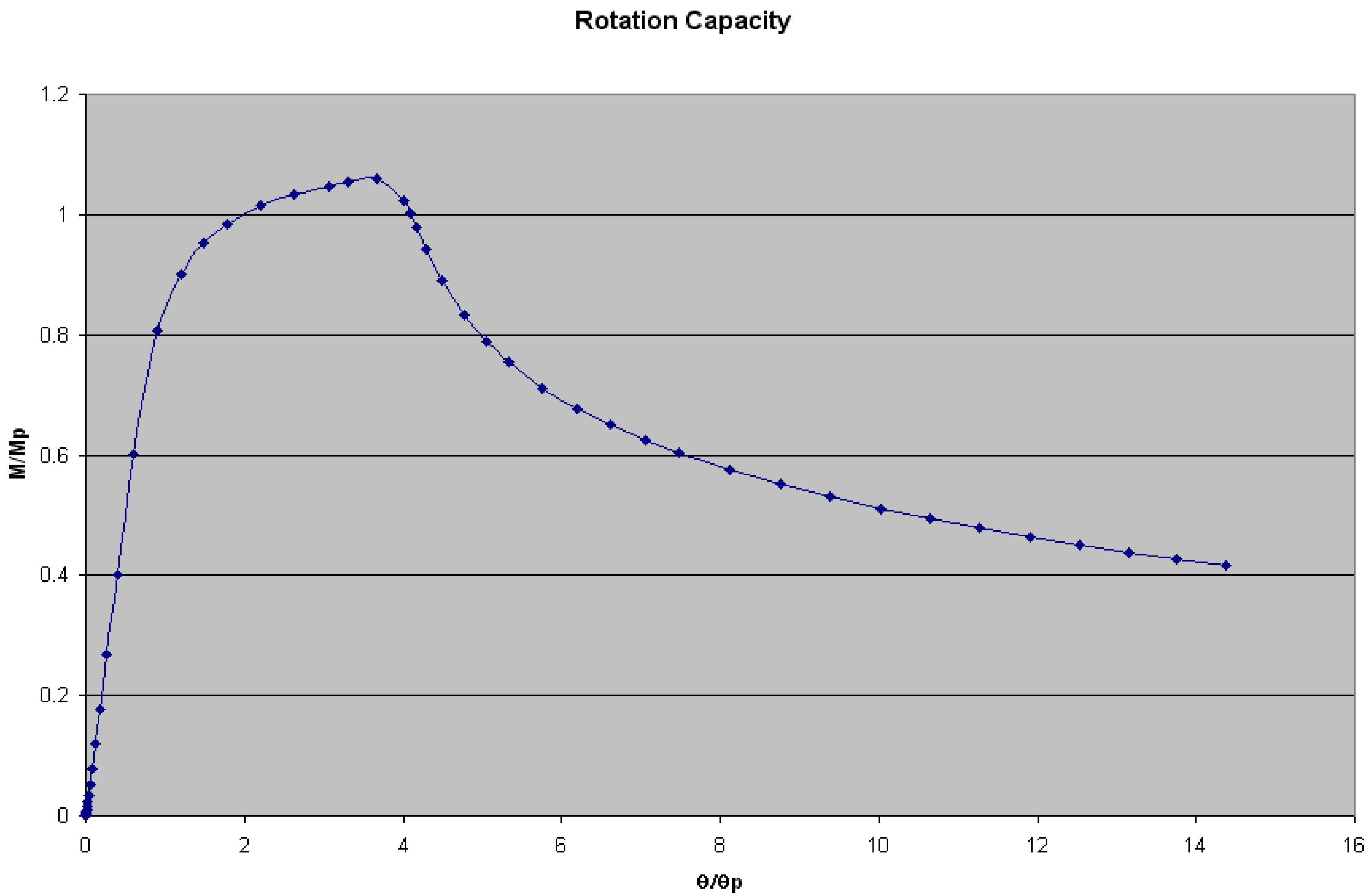

Figure B5 Moment vs. Rotation for WTEE b_f / d =1.4, t_w=1.1”

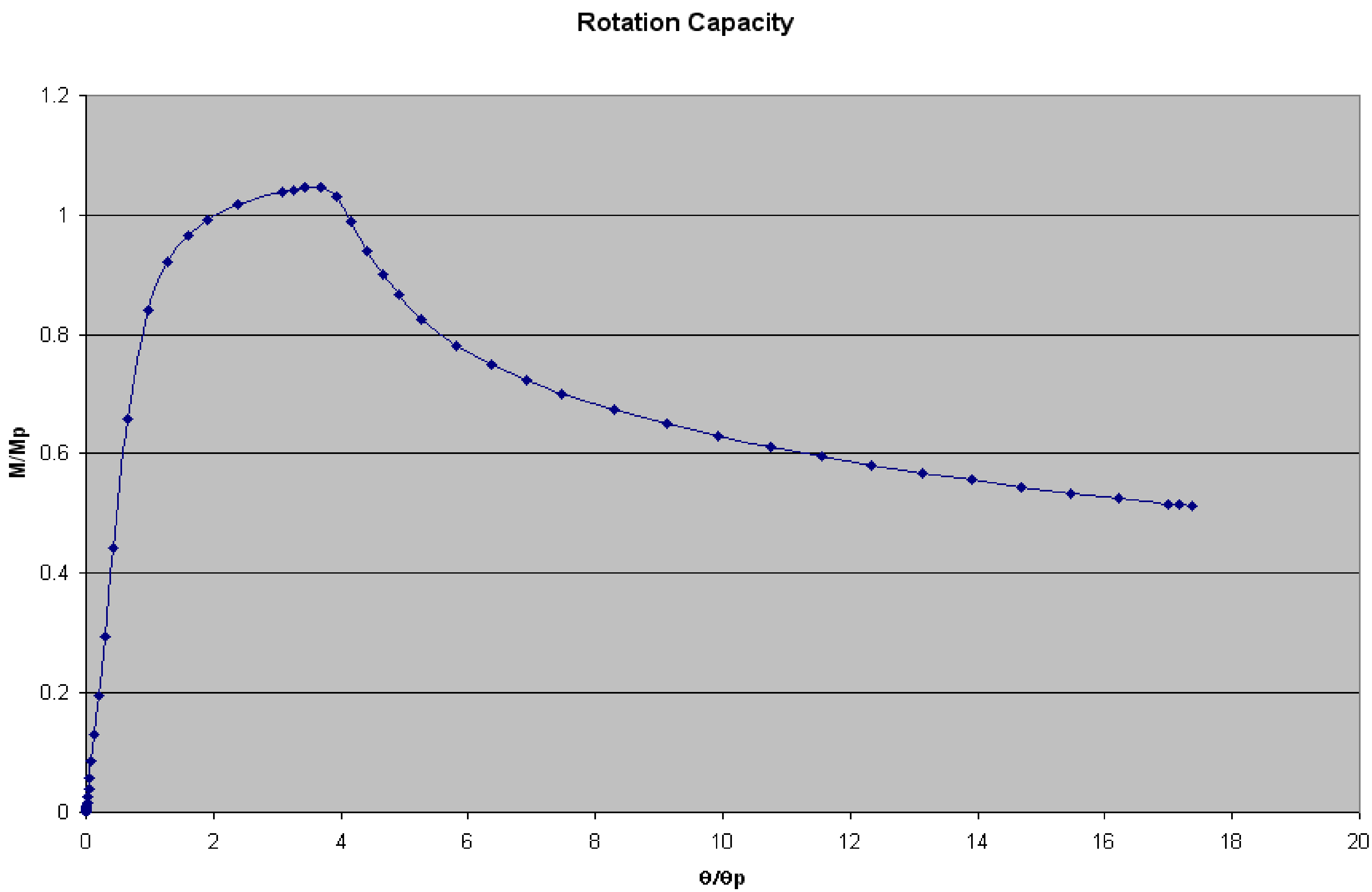

Figure B6 Moment vs. Rotation for WTEE $b_f / d = 1.6$, $t_w = 1.17$”

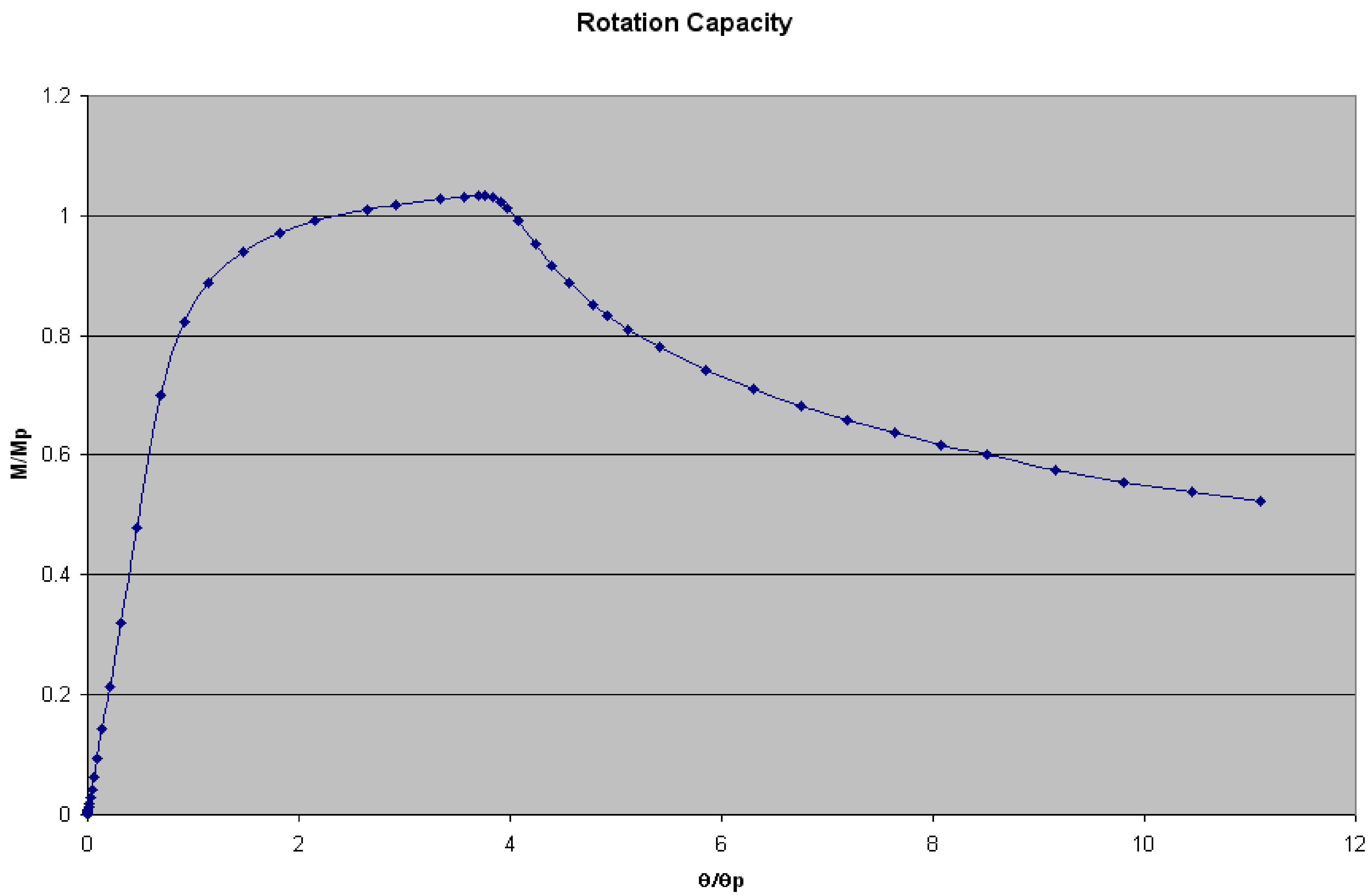

Figure B7 Moment vs. Rotation for WTEE $b_f / d = 1.8$, $t_w = 1.22"$

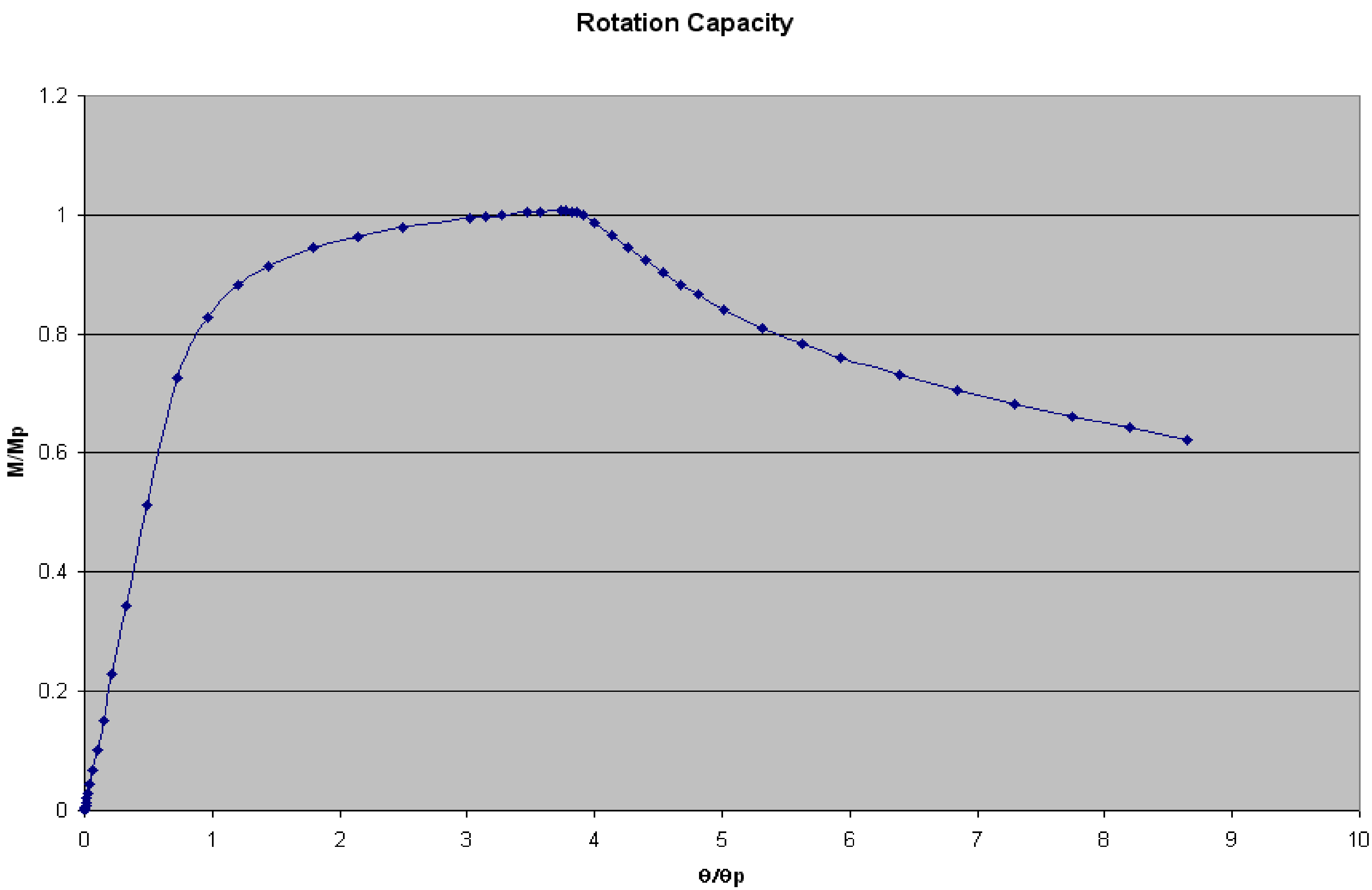

Figure B8 Moment vs. Rotation for WTEE b_f / d =2.0, t_w=1.25”

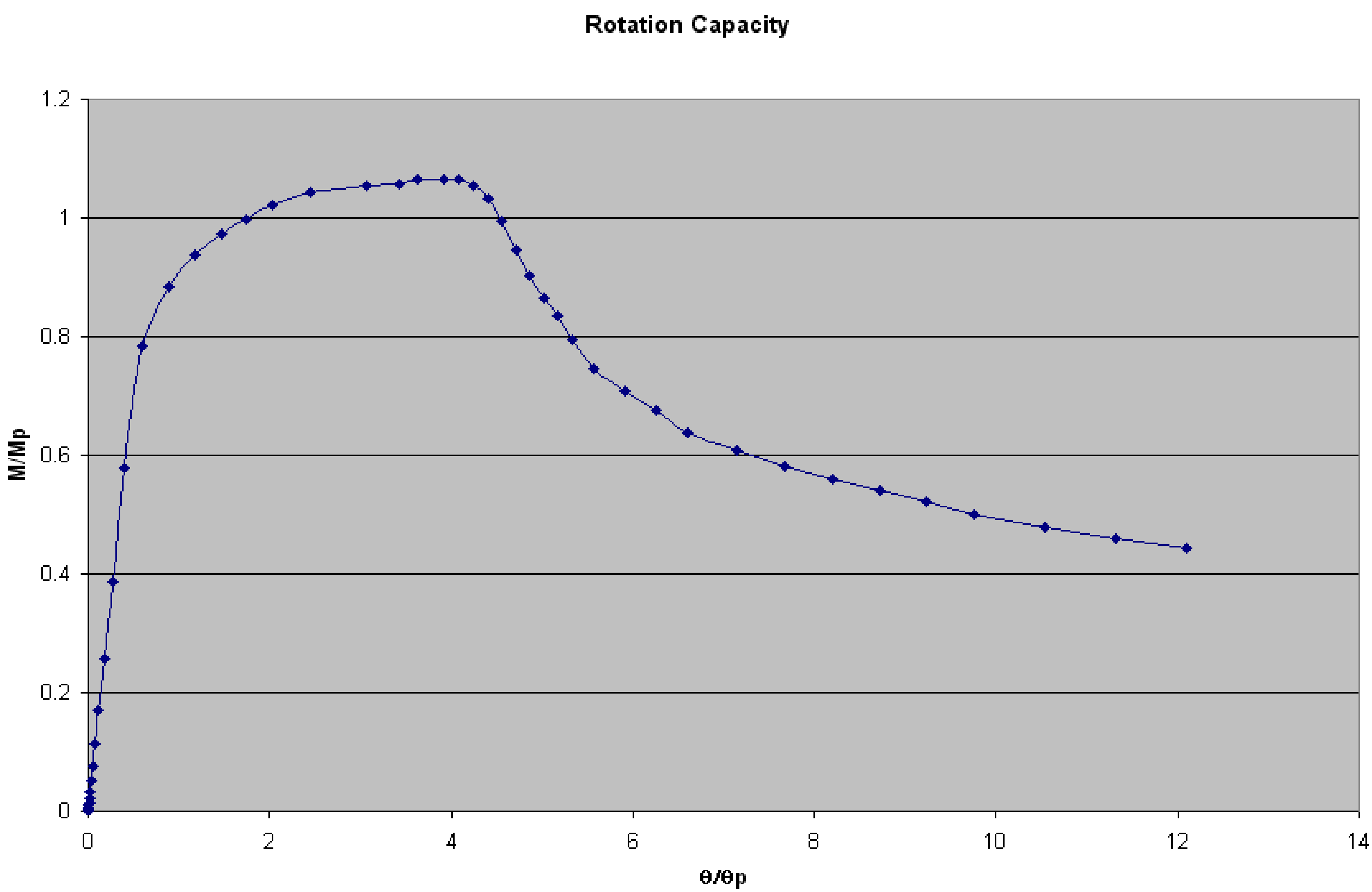

Figure B9 Moment vs. Rotation for WTEE $b_f / d = 1.4$, $t_w = 1.1$”, $\lambda_p = 1.2(65/\sqrt{F_y})$

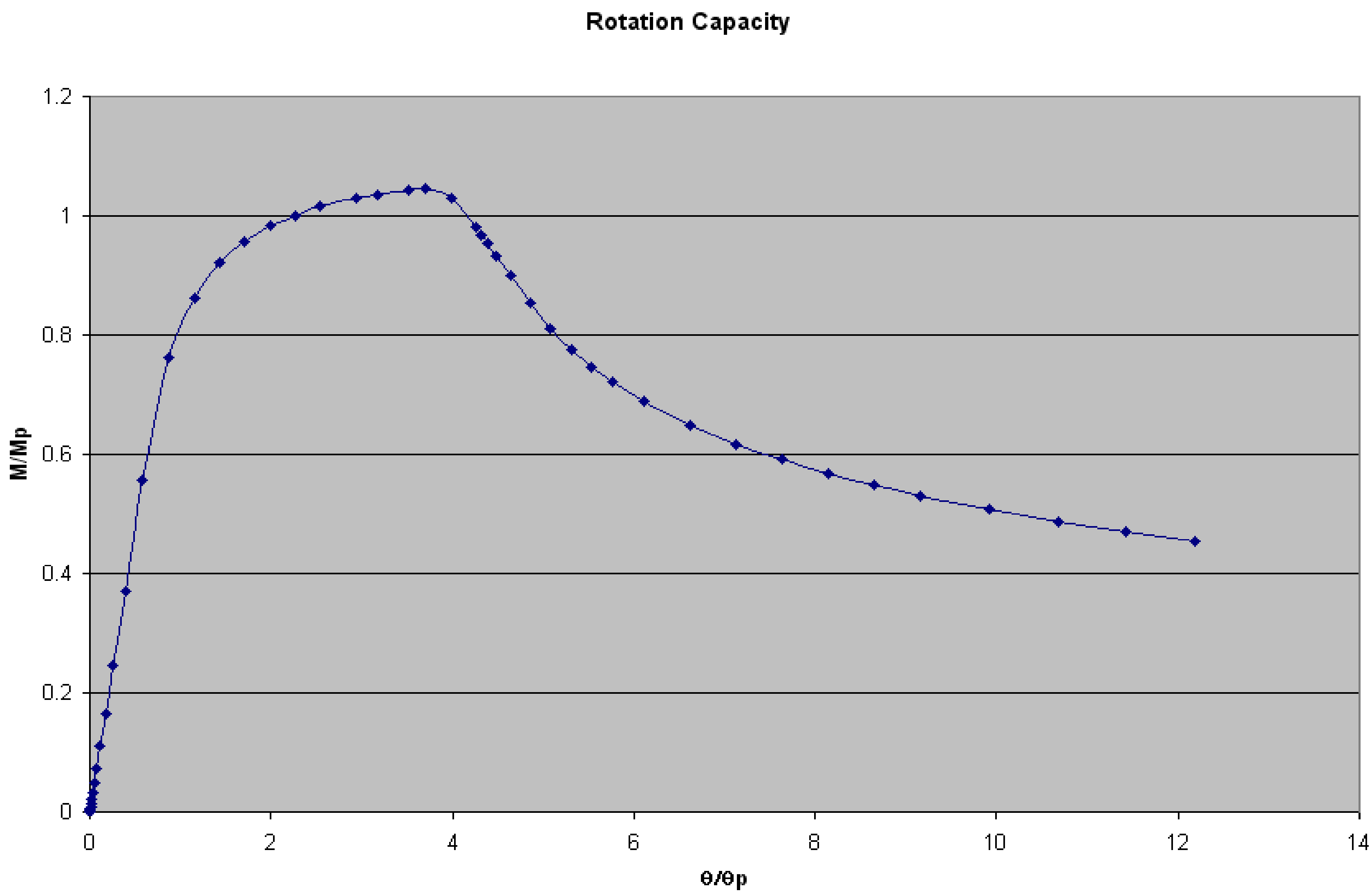

Figure B10 Moment vs. Rotation for WTEE b_f / d =1.4, t_w=1.1", $\lambda_p = 1.4(65/\sqrt{F_y})$

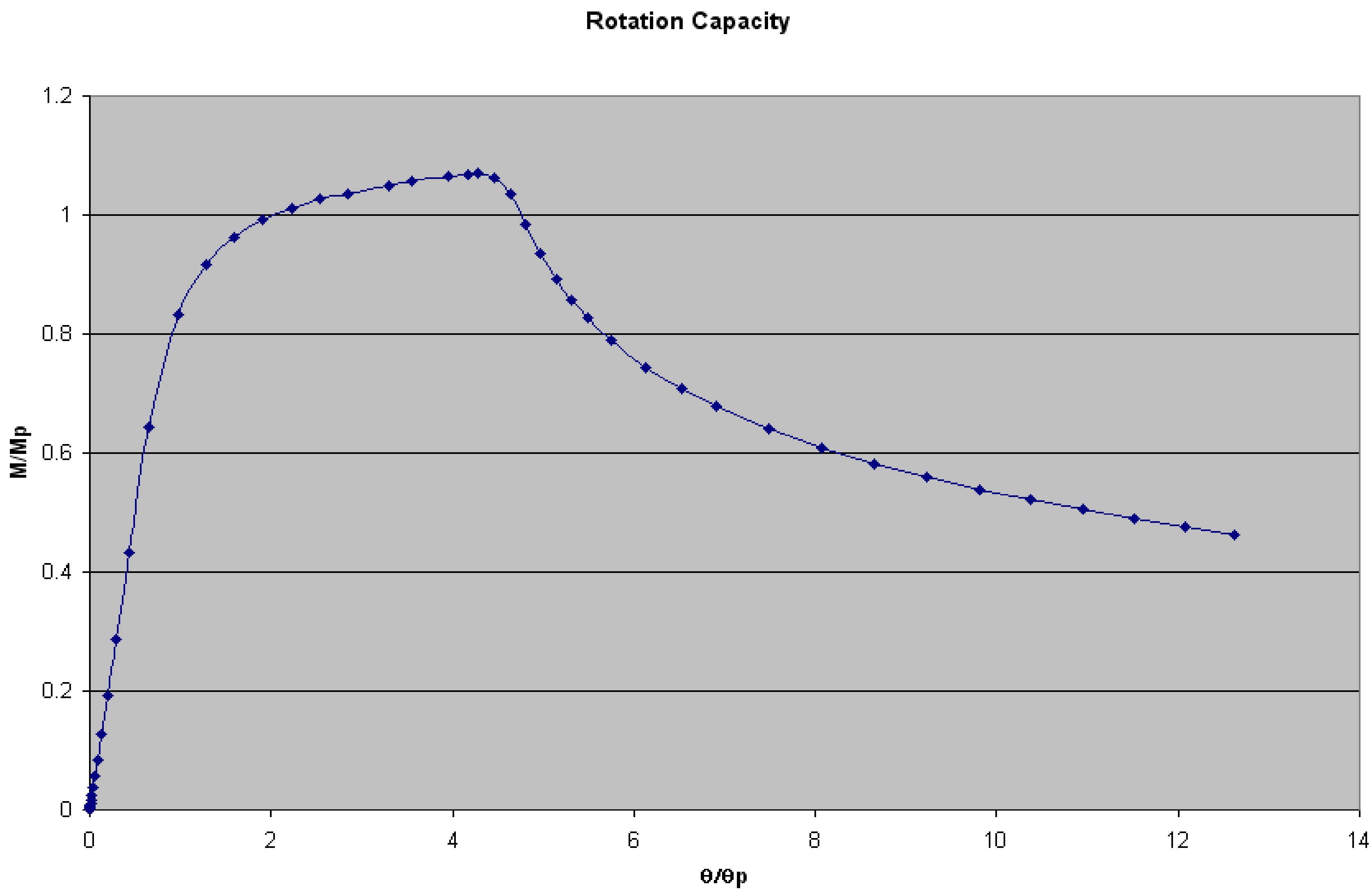

Figure B11 Moment vs. Rotation for WTEE $b_f / d = 1.6$, t_w=1.17", $\lambda_p = 1.2(65/\sqrt{F_y})$

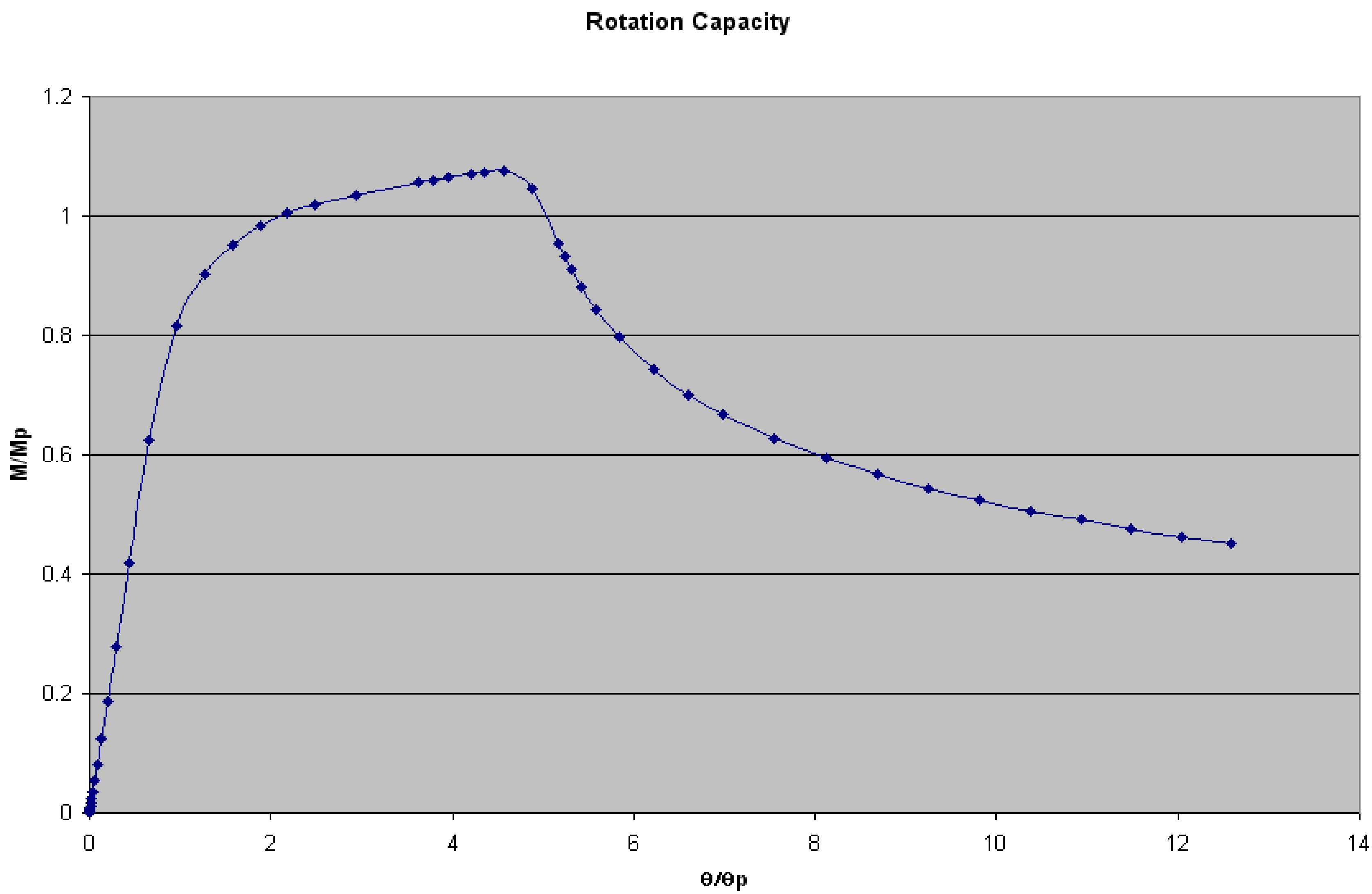

Figure B12 Moment vs. Rotation for WTEE $b_f / d = 1.6$, $t_w = 1.17$", $\lambda_p = 1.4(65/\sqrt{F_y})$

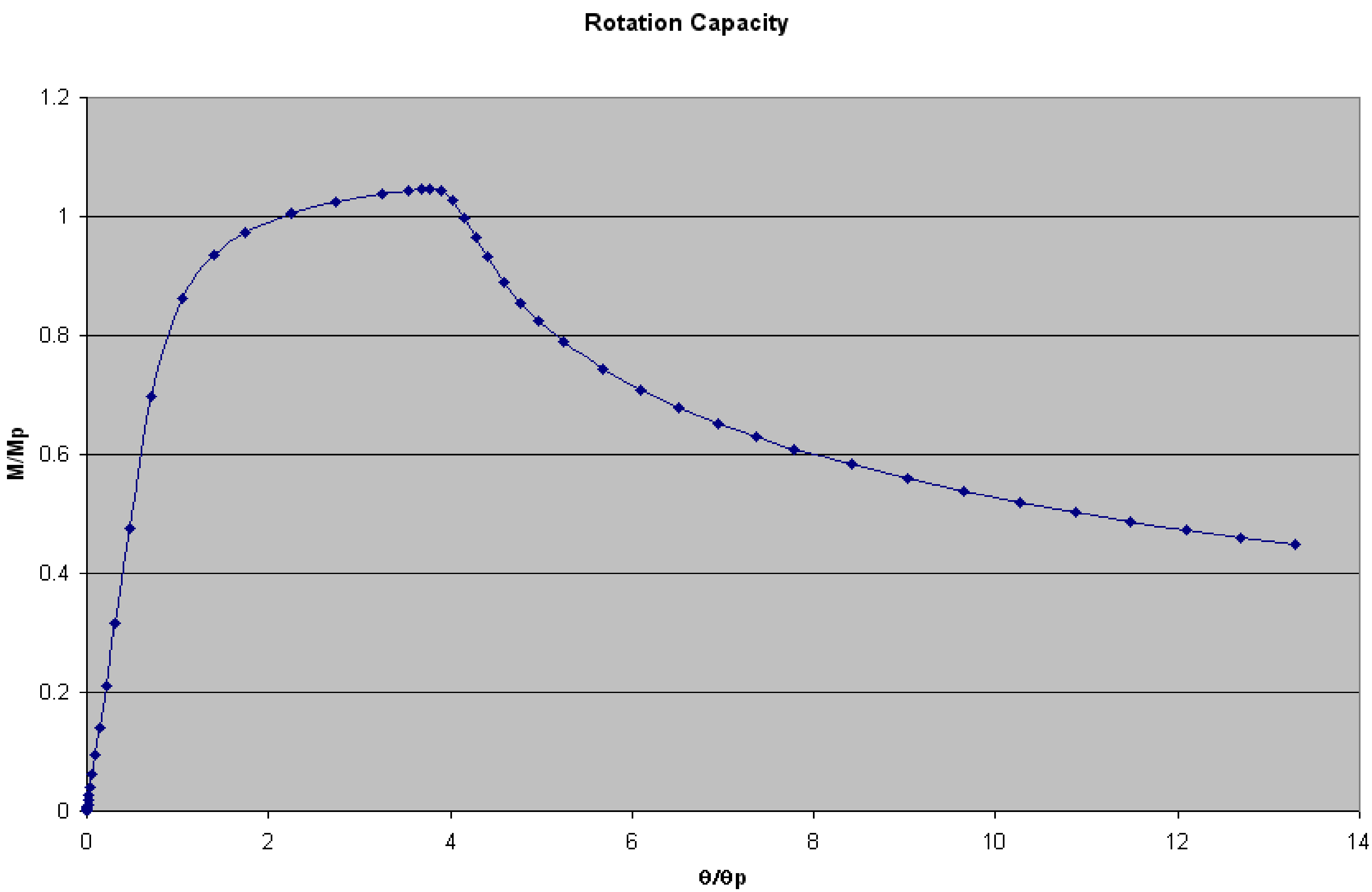

Figure B13 Moment vs. Rotation for WTEE b_f/d =1.8, t_w=1.22”, $\lambda_p = 1.2(65/\sqrt{F_y})$

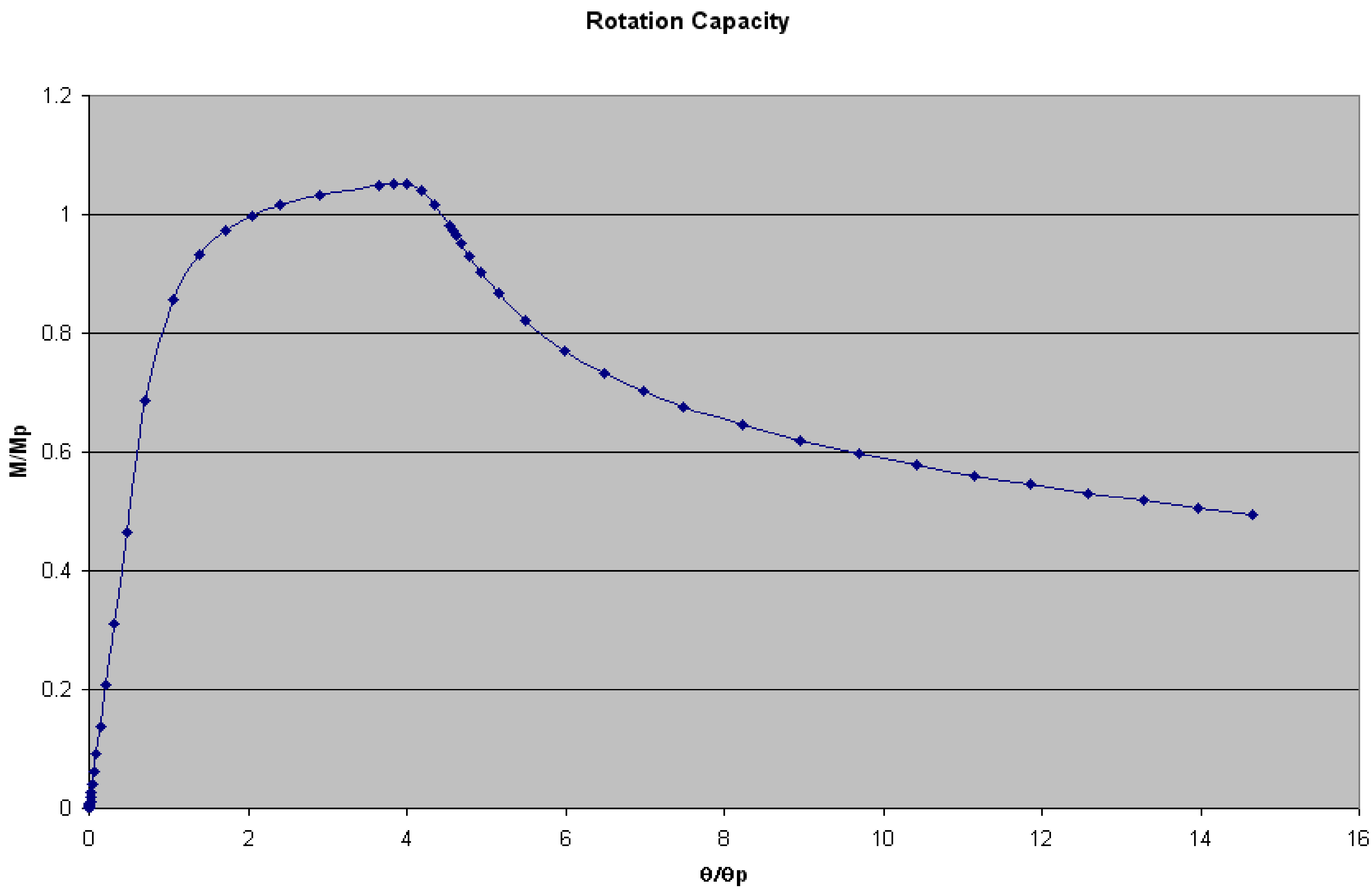

Figure B14 Moment vs. Rotation for WTEE b_f / d =1.8, t_w=1.22", $\lambda_p = 1.4(65/\sqrt{F_y})$

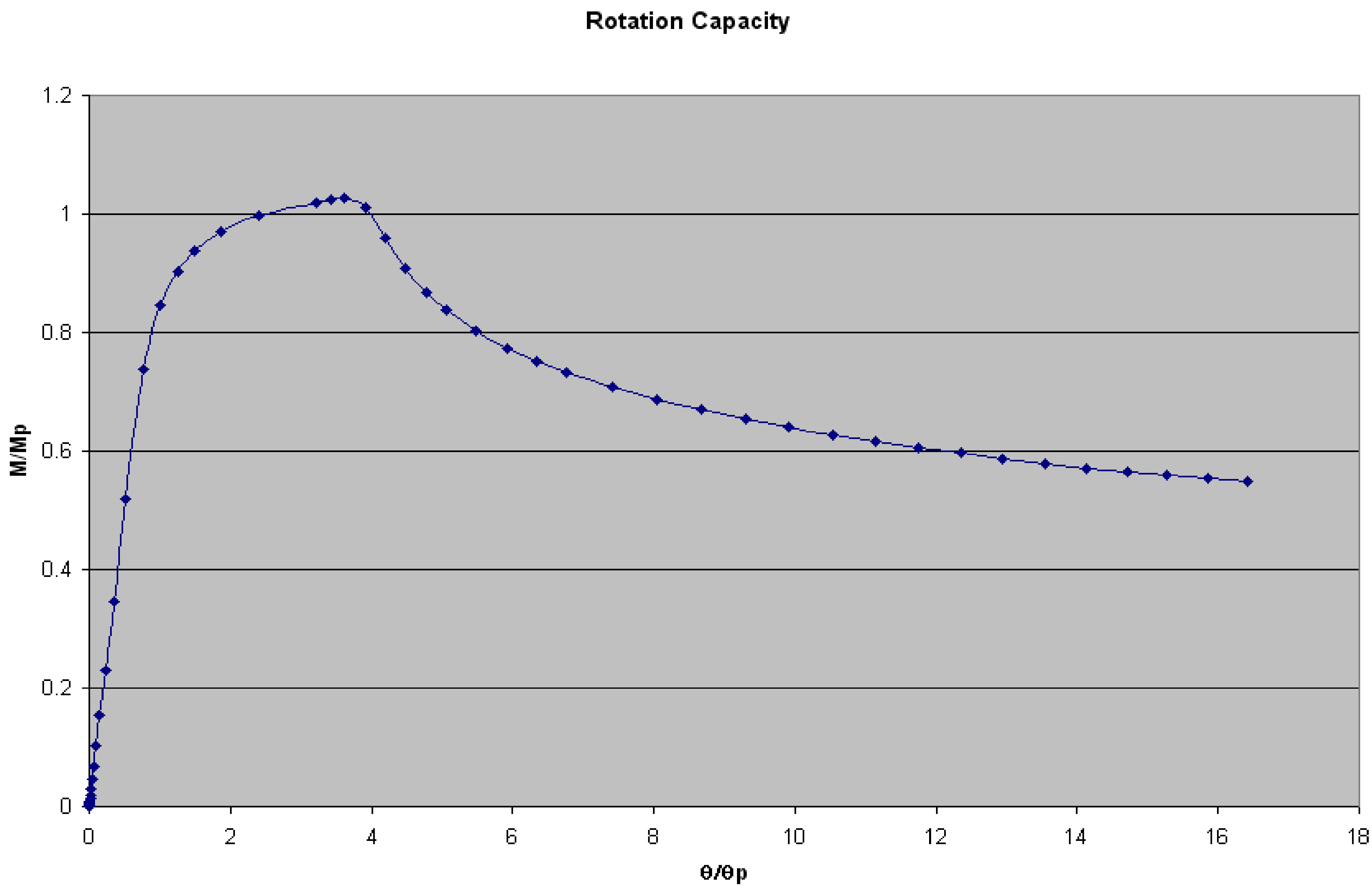

Figure B15 Moment vs. Rotation for WTEE b_f / d =2.0, t_w=1.25", $\lambda_p = 1.2(65/\sqrt{F_y})$

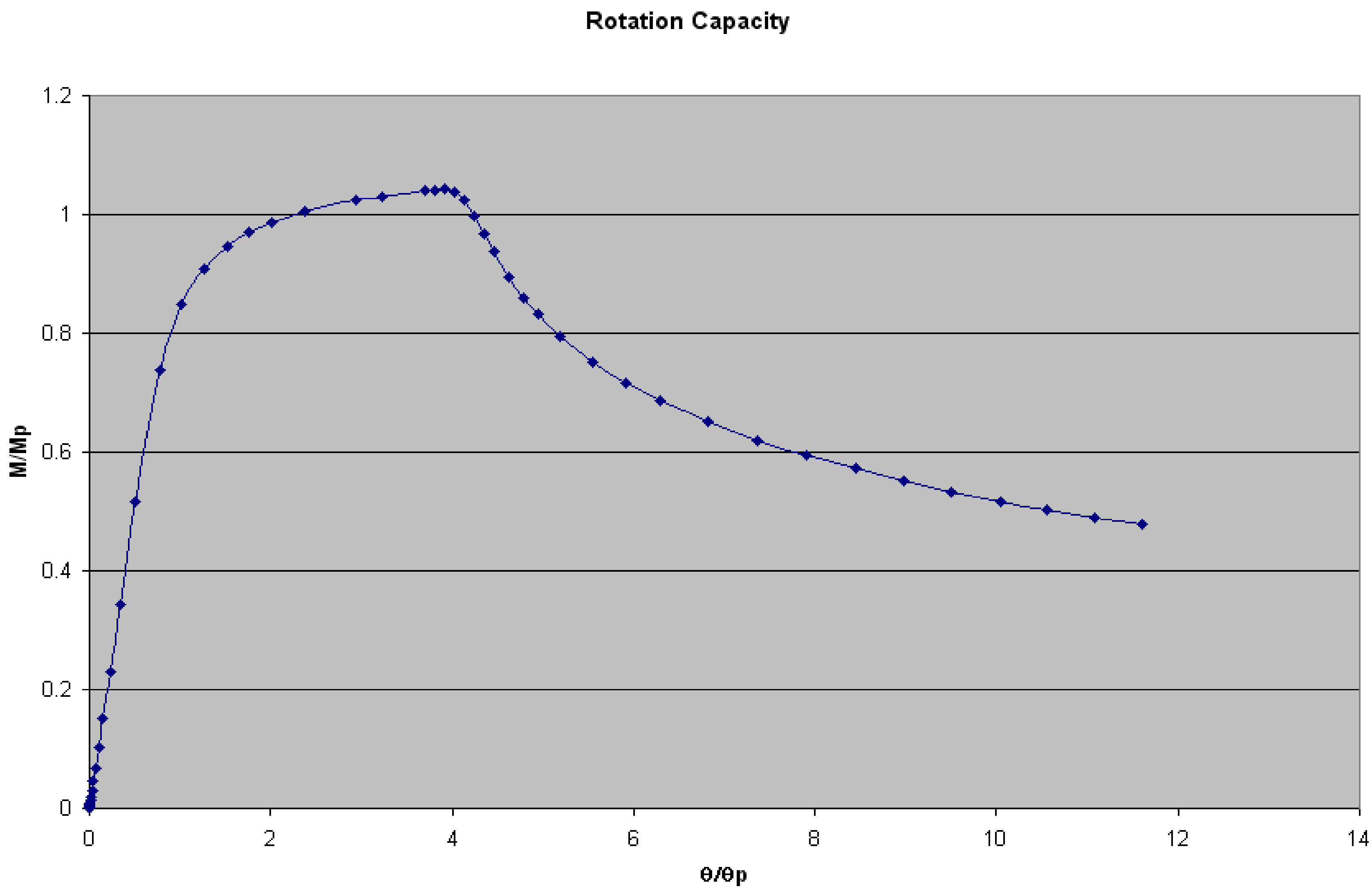

Figure B16 Moment vs. Rotation for WTEE b_f / d =2.0, t_w=1.25", $\lambda_p = 1.4(65/\sqrt{F_y})$

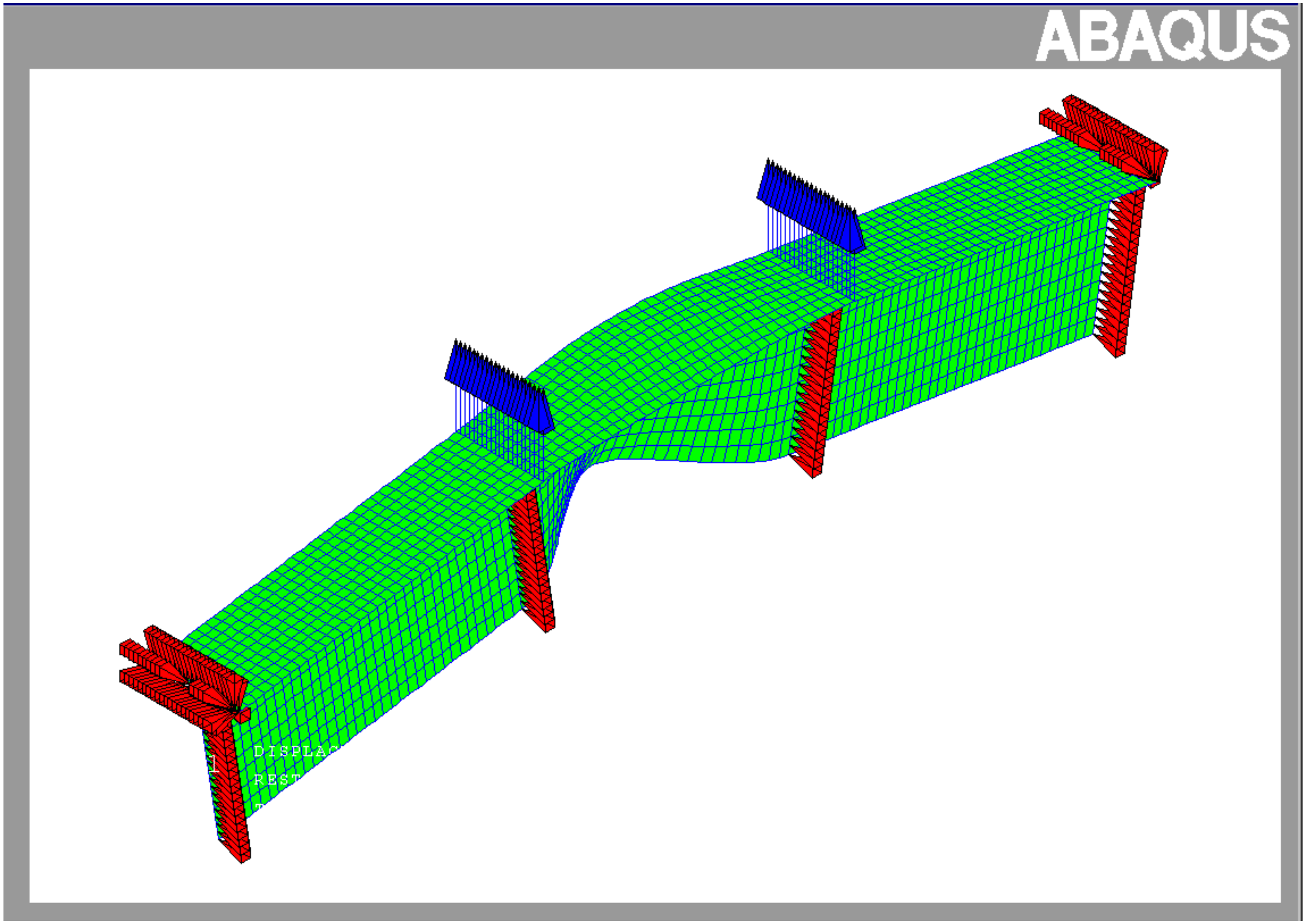

Figure B17 Boundary Conditions and Applied Loading

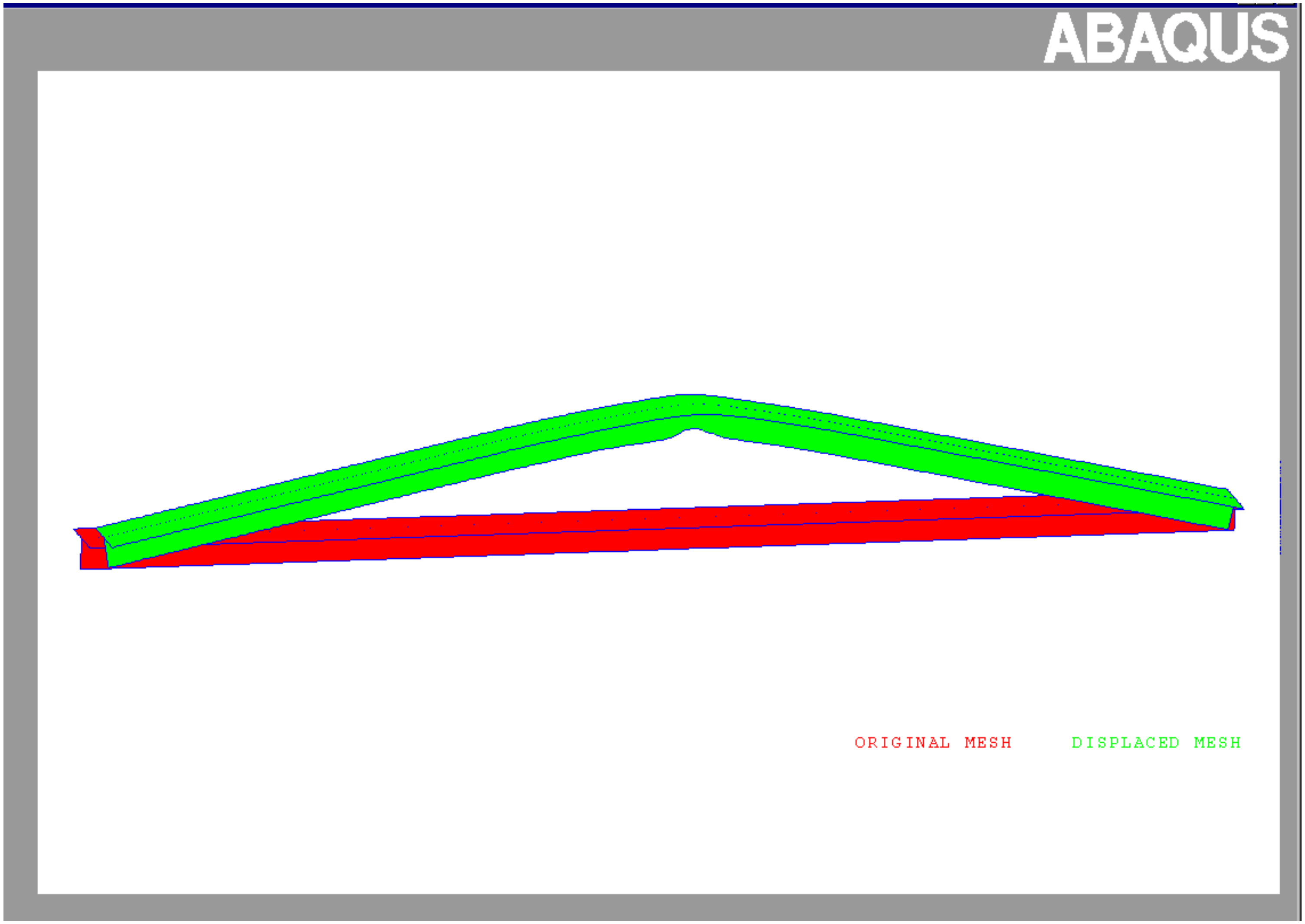

Figure B18 Typical Deformed Shape

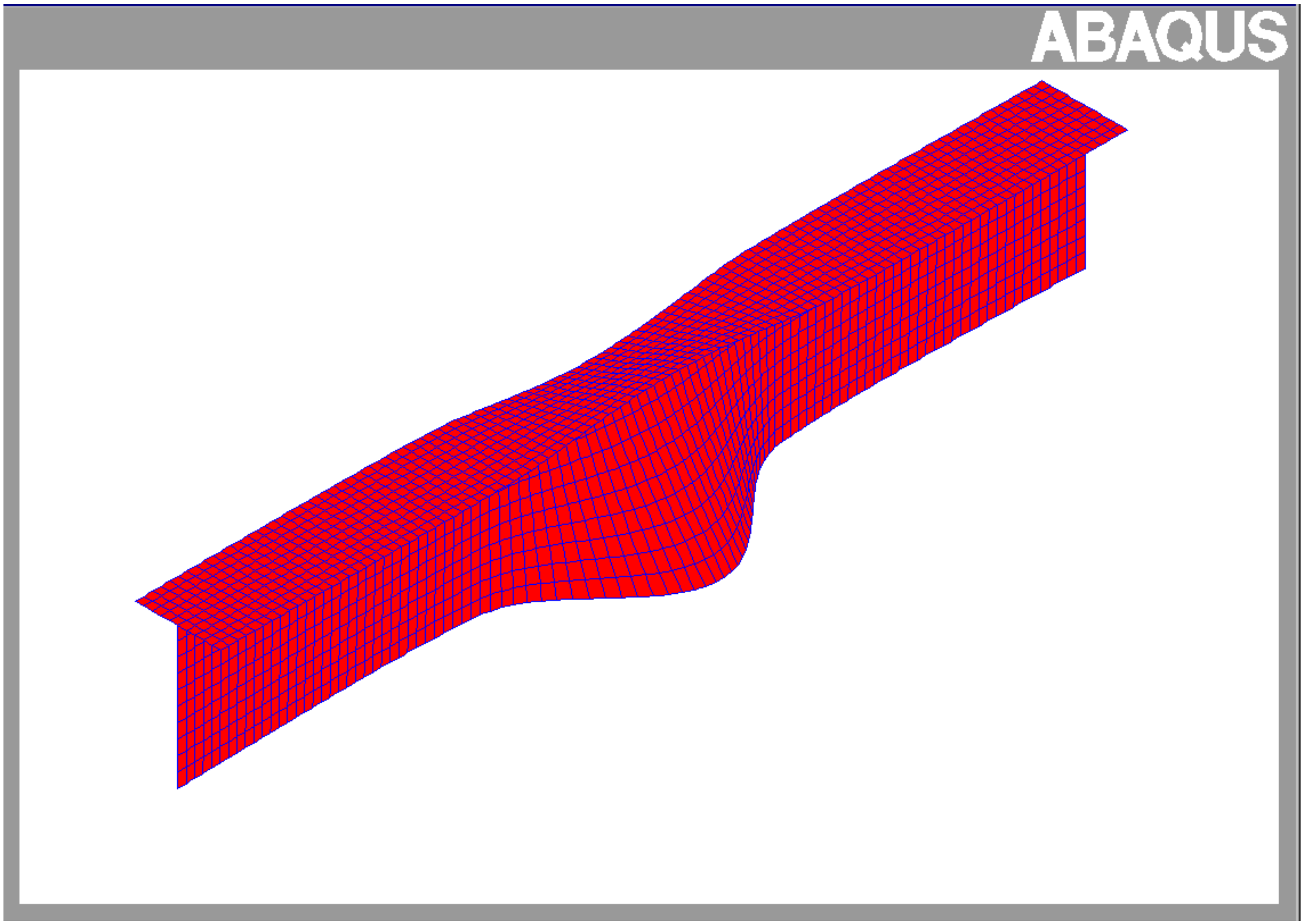

Figure B19 Typical Seed Imperfection

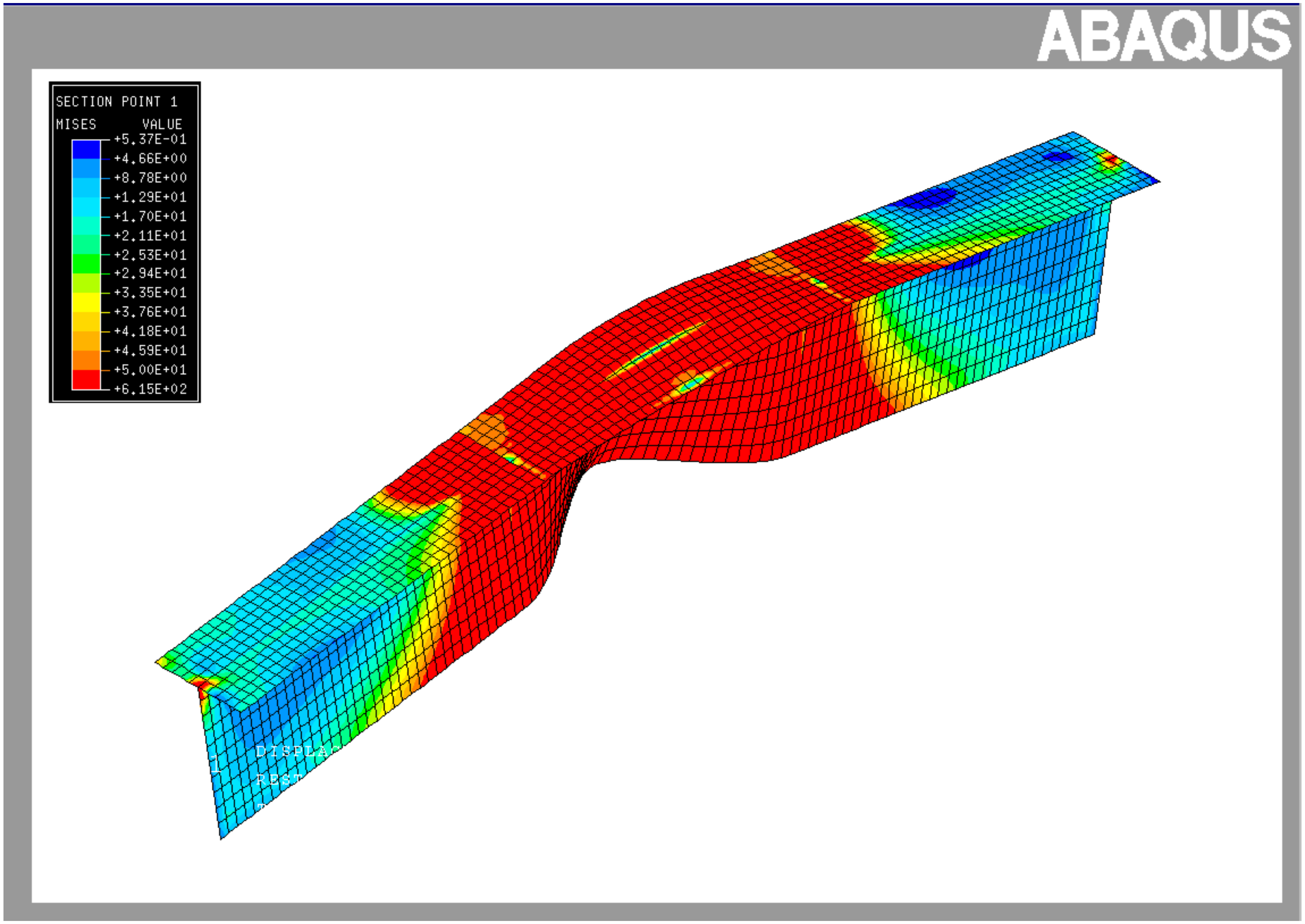

Figure B20 Von Mises Stresses for WTEE b_f / d =0.6, t_w=1.0”

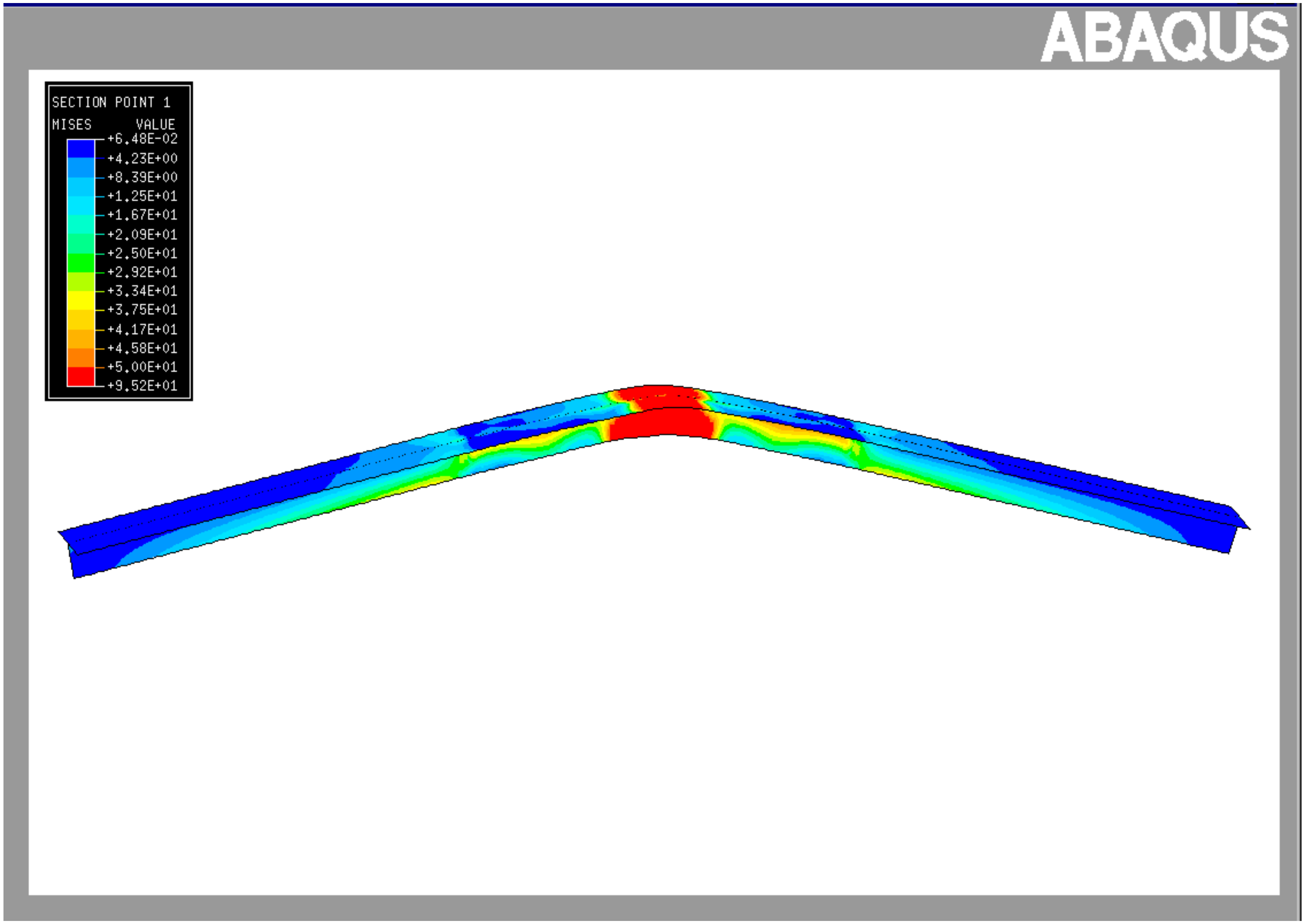

Figure B21 Von Mises Stresses for WTEE b_f / d =1.8, t_w =1.22”

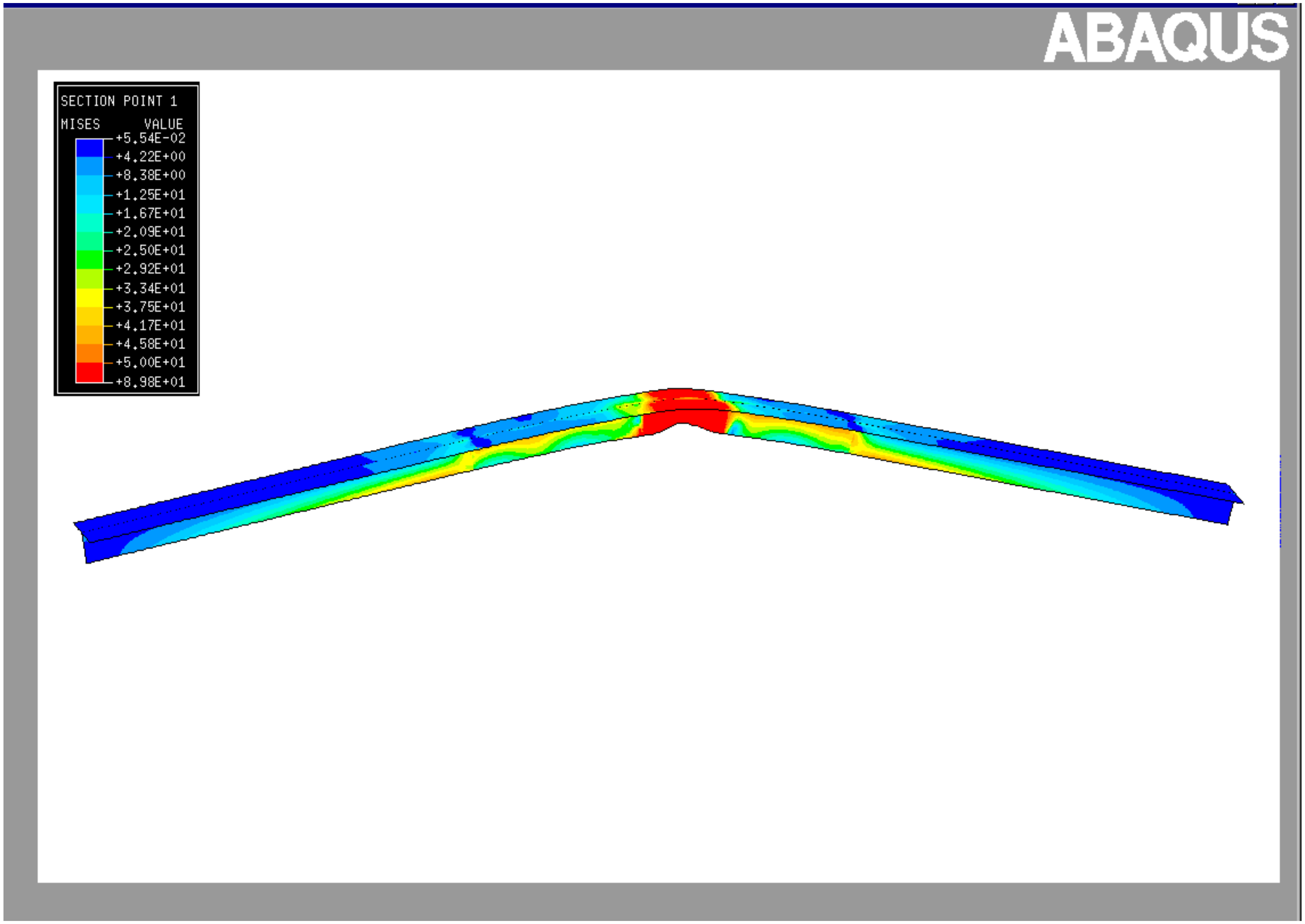

Figure B22 Von Mises Stresses for WTEE b_f / d =2.0, t_w=1.25”

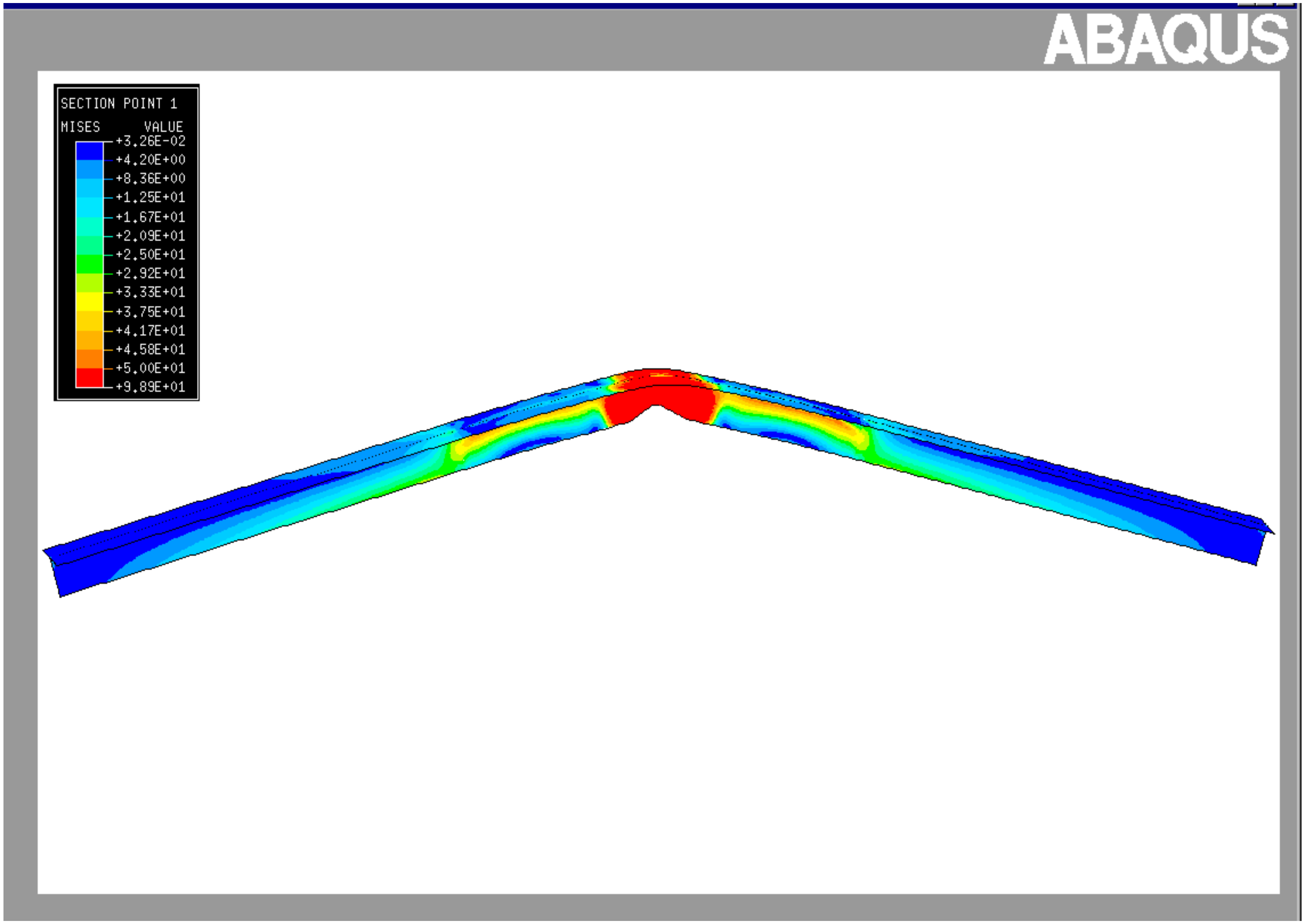

Figure B23 Von Mises Stresses for WTEE b_f / d =1.8, t_w=1.22", $\lambda_p = 1.2(65/\sqrt{F_y})$

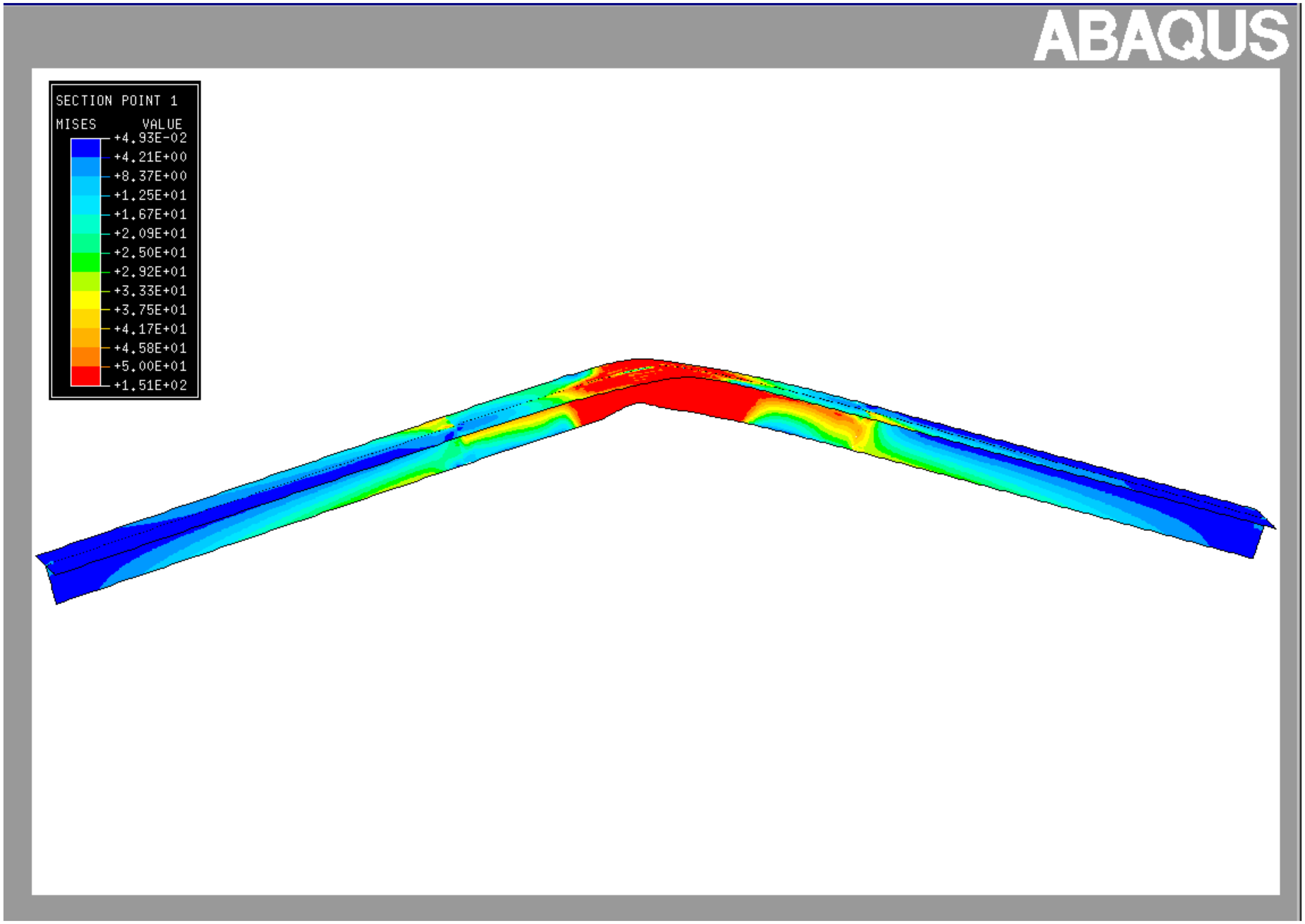

Figure B24 Von Mises Stresses for WTEE b_f / d =1.8, t_w=1.22", $\lambda_p = 1.4(65/\sqrt{F_y})$

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